A Framework for Identification and Prioritization of Materials Research for Sustainable Construction Based on an Evaluation of Durability, Economics, Sustainability and Future Availability – The Case of Marine Construction in the Long-Term Future

---

Dissertation

zur

Erlangung der naturwissenschaftlichen Doktorwürde
(Dr. sc. nat.)

vorgelegt der

Mathematisch-naturwissenschaftlichen Fakultät

der

Universität Zürich

von

Steve Kappenthuler

von

Winterthur ZH

Promotionskommission

Prof. Dr. Stefan Seeger (Vorsitz)

Prof. Dr. David Tilley

Dr. Frank Winnefeld

Zürich, 2020

“The future's not set. There's no fate but what we make for ourselves”

(John Conner in Terminator 2: Judgment Day, written by James Cameron &William Wisher Jr. 1991)

Acknowledgments

First and foremost, I would like to thank Prof. Stefan Seeger not only for the opportunity to complete my dissertation in his group, but also for giving me the freedom to shape this project from start to finish, while supporting me along the way. His regular feedback and guidance kept this project going in the right direction and, especially during the beginning of my work, prevented me from making a couple of choices that would have led to complications in the long run.

Second, I want to thank Dr. Sandro Olveira for the great collaborations within the business chemistry group concerning research and teaching, as well as for the numerous work and non-work related conversations held over way to many cups of coffee.

A big thank you is also in order for all other members of the Seeger group for contributing to an enjoyable, friendly and open working environment.

Concerning the contents of this dissertation, I want to express my gratitude towards all Experts from around the world who took their time to talk to me and participated in this study. Without their input it would not have been possible to complete this project.

Amongst these experts, a special thank you goes to Dr. Frank Winnefeld, who not only spent multiple sessions with me discussing the performance of the various concretes, but also kindly agreed to serve as an external member on my doctoral committee.

In this respect, I would also like to thank Prof. David Tilley for taking his time to serve on my doctoral committee.

Finally, I am very grateful for my family, who unconditionally supported me during my entire PhD, and my friends, without whom my life would be rather boring.

Abstract

Increasing global population and growing rates of urbanization have led to strongly increasing demand for infrastructure worldwide over the past decades. At the same time, increasing scarcity of global resources and noticeable impacts from climate change have strengthened public advocacy of environmental protection measures which are being more and more strictly enforced by governments around the world. As a major source of environmental impacts, the construction industry is moving towards more sustainable construction strategies. As materials have a large effect on the overall durability, economics and sustainability of a structure, the systematic selection of optimal materials for individual components is a commonly used approach. Consequently, various fields of research are aiming to improve the sustainability of employed construction materials. However, considering the accelerated depletion of global resources, it is imperative from a sustainability perspective to develop an understanding of the long-term availability of construction materials before engaging in costly research to improve their performance in one area or another.

To address these issues, a framework was developed in the scope of this dissertation to support the identification and prioritization of research projects and policy measures aiming at increasing the overall sustainability of the construction industry. The framework is based on a holistic ranking of materials' technical, economic and environmental performance as well as the future availability of their respective raw material constituents. The detailed ranking enables a comparison of the strengths and weaknesses of existing as well as newly developed materials. Each of the 27 attributes included in the framework is measured on a precisely defined scale, which is based on literature and expert data. Thus, an objective and efficient evaluation of individual materials by practitioners and researchers is possible.

The framework was applied to the specific case of marine construction and used to evaluate and rank 48 different materials covering the categories of metals, fiber reinforced polymer composites, concretes and timbers. For each material category various established and more recently developed material types were included. Marine construction (specifically floating infrastructure) was identified as an industry that has a high growth potential in the longer term, based on a detailed analysis of current and predicted large-scale global developments (so-called megatrends).

Combining the evaluation of material performance with the analysis of factors affecting the respective long-term availability, specific areas of materials research and policy measures with considerable long-term potential to improve the economic and environmental sustainability of the marine construction industry were identified and prioritized for each material category. Overall, timbers, reinforced concretes from blended and alternative cements, carbon fiber reinforced thermoplastic composites, as well as carbon steels were identified as the highest-ranking materials. Highlighted promising improvement approaches include, amongst others, the development of environmentally benign protective coatings, improved recycling technologies, incentivization of the use of recycled materials and adaption of codes and regulations to recently published experimental findings.

Zusammenfassung

Eine wachsende globale Bevölkerung und steigende Urbanisationsraten haben in den letzten Jahrzehnten zu einem starken Anstieg der weltweiten Nachfrage nach Infrastruktur geführt. Gleichzeitig haben die steigende Knappheit globaler Resourcen und merkbare Auswirkungen des Klimawandels das öffentliche Interesse an Umweltschutzmassnahmen gestärkt. Diese werden von vielen Regierungen weltweit auch immer strikter durchgesetzt. Die Bauindustrie, welche eine bedeutende Quelle solcher Umweltbelastungen ist, bewegt sich daher immer weiter in Richtung nachhaltigerer Baustrategien. Da die eingesetzten Materialien ein grossen Einfluss auf die gesamte Lebensdauer, Wirtschaftlichkeit und Nachhaltigkeit eines Bauwerk haben, stellt die systematische Selektion optimaler Materialien für individuelle Komponenten einen oft umgesetzten Ansatz dar. Demzufolge verfolgen unterschiedlichste Forschungsfelder das Ziel, die Nachhaltigkeit der eingesetzten Materialien zu verbessern. In Anbetracht der immer schnelleren Erschöpfung globaler Resourcen ist es jedoch, von einer Nachhaltigkeitsperspektive aus gesehen, zwingend notwendig, ein Verständnis über die langfristige Verfügbarkeit von Baumaterialien aufzubauen, bevor aufwendige Forschung betrieben wird, um gewisse Eigenschaften dieser Materialien zu verbessern.

Um diese Probleme anzugehen, wurde im Rahmen dieser Dissertation ein Bewertungssystem entwickelt, welches die Identifikation und Priorisierung von Forschungsprojekten und politischen Massnahmen unterstützt, die auf eine Verbesserung der gesamtheitlichen Nachhaltigkeit der Bauindustrie abzielen. Das System basiert auf einer holistischen Bewertung der technischen, wirtschaftlichen und umweltbezogenen Eigenschaften unterschiedlicher Materialien, sowie der zukünftigen Verfügbarkeit der jeweiligen Rohmaterialkomponenten. Die detaillierte Bewertung erlaubt es, die Stärken und Schwächen etablierter als auch neu entwickelter Materialien zu vergleichen. Jedes der 27 Attribute, welche Bestandteil des Systems sind, wird anhand einer präzise definierten Skala gemessen, welche auf Fachliteratur und Expertenmeinungen basiert ist. Somit ist eine objektive und effiziente Evaluation individueller Materialen durch Praktiker und Forscher möglich.

Das Framework wurde auf den spezifischen Fall des Marinebaus angewendet und eingesetzt, um 48 unterschiedliche Materialien zu evaluieren und zu bewerten, welche die Kategorien Metalle, Faserverbundswerkstoffe, Beton, und Holz abdecken. Für jede Materialkategorie wurden verschiedene etablierte und auch neulich entwickelte Materialtypen untersucht. Marinebau (genauer, schwimmende Infrastruktur) wurde, basierend auf einer detaillierten

Analyse aktueller und prognostizierter globaler Entwicklungen (sogenannte Megatrends), als ein Industriezweig identifiziert, welcher langfristig ein hohes Wachstumspotentzial hat.

Durch die Kombination der Evaluation der Eigenschaften der Materialien mit der Analyse der Faktoren, welche die langfristige Verfügbarkeit der jeweiligen Rohmaterialen beeinflussen, wurden für jede Materialkategorie spezifische Felder der Materialfoschung und unterschiedliche politische Massnahmen identifiziert und priorisiert, welche ein erhebliches, langfristiges Potential haben, die wirtschaftliche und auch ökologische Nachhaltigkeit der Marinebau-Industrie zu verbessern. Insgesamt wurden, Holz, Beton aus Mischzement und alternativen Zementen, Carbonfaser verstärkte thermoplastische Verbundswerkstoffe, sowie Stahl als am höchsten bewertete Materialien identifiziert. Priorisierte Verbesserungsansätze beinhalten unter anderem die Entwicklung umweltfreundlicher Schutzbeschichtungen, verbesserte Recyclingtechnologien, die Incentivierung der Nutzung von recyclierten Materialien, sowie die anpassung existierender Richtlinien und Vorschriften an aktuell publizierte experimentelle Erkentnisse.

List of Publications

The research carried out in scope of this dissertation has resulted in the following publications and contributions, parts of which are reproduced in this manuscript:

Peer reviewed publications:

- **P3**
  S. Kappenthuler, S. Seeger
  Addressing global environmental megatrends by decoupling the causal chain through floating infrastructure
  Futures, **113** (2019)
- **P2**
  S. Kappenthuler, S. Seeger
  From resources to research - A framework for identification and prioritization of materials research for sustainable construction
  Materials Today Sustainability (2019)
- **P1**
  S. Kappenthuler, S. Olveira, J. Wehrli, S. Seeger
  Environmental assessment of alternative methanesulfonic acid production using direct activation of methane
  Journal of Cleaner Production, **202**, 1179-1191 (2018)

Submitted Manuscripts:

- **S3**
  S. Kappenthuler, S. Seeger
  Assessing the Long-Term Potential of Fiber Reinforced Polymer Composites for Sustainable Marine Construction
  Ocean Engineering and Marine Energy, Submitted 07.11.2019
- **S2**
  S. Kappenthuler, S. Seeger
  Comparative Assessment of Alternative Cements and Rebar for Use in Sustainable Construction
  Cement and Concrete Composites, Submitted 13.08.2019

- **S1**
  S. Kappenthuler, S. Seeger
  Holistic Evaluation of the Suitability of Metal Alloys for Sustainable Marine Construction from a Technical, Economic and Availability Perspective
  Ocean Engineering, Submitted 30.07.2019

Completed Manuscripts

- **M2**
  S. Kappenthuler, S. Seeger
  Evaluation and Comparison of Materials for Use in Sustainable Marine Construction in the Long-Term Future.
- **M1**
  S. Kappenthuler, S. Seeger
  Comparative Assessment of Timber and Non-Renewable Construction Materials for the Sustainable Use in Marine Environments.

Contributions at Conferences

- S. Kappenthuler, S. Seeger
  A framework for identification and prioritization of material research for sustainable construction including a holistic evaluation of long-term commercial applicability
  Oral presentation, *4th Green & Sustainable Chemistry Conference*, Dresden (Germany), May 5th-8th, 2019.
- S. Kappenthuler, S. Seeger
  A holistic ranking of construction materials for marine environments in the long term future
  Poster presentation, *19th International Congress on Marine Corrosion and Fouling*, Melbourne (FLA, USA), June 24th-29th, 2018.

Abbreviations

AA	Aluminum alloys
AAC	Alkali activated cement
ADV	Advanced economies
AHP	Analytical Hierarchy Process
BC	Blended cement
BF	Basalt fiber
BFRP	Basalt fiber reinforced polymer
CF	Carbon fiber
CFRP	Carbon fiber reinforced polymer
CS	Carbon steel
DEV	Developing economies
DSM	Deep sea mining
E	Epoxy
EI	Environmental impact
EIP	Environmental impact point
EM	Emerging economies
EWEA	European Wind Energy Association
FA	Fly ash
FAO	Food and Agriculture Organization of the United Nations
FRPC	Fiber reinforced polymer composite
FU	Functional unit
GBFS	Ground, granulated blast furnace slag
GDP	Gross domestic product

GF	Glass fiber
GFRP	Glass fiber reinforced polymer
GHG	Greenhouse gas
GMO	Genetically modified organisms
HHI	Herfindahl-Hirschman-Index
IEA	International Energy Agency
IMF	International Monetary Fund
IPCC	International Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
MCDA	Multi criteria decision analysis
MIC	Microbially induced corrosion
NF	Natural fiber
NFRP	Natural fiber reinforced polymer
Ni-Cu	Nickel-copper alloys
OTEC	Ocean thermal energy conversion
PE	Polyester
PPP	Purchasing power parity
SCC	Stress corrosion cracking
SCM	Supplementary cementitious material
SFT	Submerged floating tunnel
SS	Stainless steel
SSV	Surface support vessel
TiA	Titanium alloys

TP	Thermoplastic
TRAM	Technological Research Association of Megafloat
UN	United Nations
USGS	U.S. Geological Survey
UV	Ultraviolet
VE	Vinylester

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation and Background

In the coming decades humanity will be confronted with a number of complex challenges affecting the prosperity and livelihood of billions of people around the globe. Through the study of current developments in individual, social or technological structures it is possible, to a certain extent, to predict what these challenges may be and which developments present the main underlying drivers. The analysis of such so-called megatrends has been extensively used by industry as well as academia to, for instance, develop long term business strategies, drive investment decisions or properly prioritize research projects.

In the scope of this thesis a comprehensive chain of cause and effect connecting individual trends and megatrends was developed, with the goal of identifying the major issues that will arise in the coming decades, determining an industry capable of addressing these issues on a global scale and developing a framework to allow this industry to develop solutions effectively by focusing research and policy efforts towards projects and concepts with the potential for promising results on a large scale and also for a long period of time.

In other words, the goal is to move from global developments to individual research projects or policy developments focusing on a specific industry and evaluate the potential results and consequences of these approaches if they were to be applied on a global scale.

Concerning global megatrends, the unprecedented increase in global population and the consequentially increasing pressure on available resources such as food, water, minerals or even space were identified as the main drivers for many if not all of the major challenges which humanity will be facing in the coming decades. A major consequence of these increasing levels of global resource demand is climate change and all its associated effects. At the center of these developments lies one of the largest and oldest industries in the world, the construction industry.

The construction industry's growth is directly affected by the same key drivers as mentioned above, it is responsible for a large proportion of global greenhouse gas (GHG) emissions and waste production as well as being a major consumer of mineral and energy resources. Consequently, changes within this industry will lead to potentially significant effects on a global scale. One high-level development that was identified in the course of this thesis was the increasing use of floating infrastructure (a form of marine construction) as a mid- to long-term climate change adaption strategy. A major factor not only determining the long-term success and profitability of the construction industry, but also greatly influencing the industries overall effect on the evaluated megatrends are the actual materials used for construction.

Therefore, the central part of this thesis consists of the development a framework, intended to aid the process of identifying promising areas for research and development focusing on construction materials and prioritizing them according to their impact on the overall sustainability of the industry, as well as their potential for long-term commercial applicability. The framework is based on a holistic ranking of materials according to their technical, economic and environmental performance in a desired environment and for a wide range of specific applications or components. In the light of increasing global scarcity of various materials as well as dwindling resource stocks, the factors affecting the long-term availability of the raw materials required for production of each material are also assessed. This detailed evaluation enables a comparison of the strengths and weaknesses of existing as well as newly developed materials. Each of the 27 attributes included in the framework is measured on a precisely defined scale, which is based on literature and expert data. Thus, an objective and efficient evaluation of individual materials by practitioners and researchers is possible. Combining the evaluation of material performance with the analysis of factors affecting the respective long-term availability, it is possible to focus funding on specific areas and approaches where research and policy measures have the highest probability of providing long-term improvements to the construction industry.

The application of this framework to the specific case of marine construction serves as a demonstration of the various possibilities provided by the framework. In total, 48 different materials, containing metals, concretes, fiber reinforced polymer composites and timbers, were evaluated and ranked according to their long-term potential for use in sustainable marine construction. By focusing on the identified weaknesses of the individual materials promising areas of research which support the sustainable use of these materials were identified and discussed.

1.2 Structure of Thesis

Chapter 2 focuses on the identification, classification and connection of megatrends, as well as the reasoning behind the selection of the construction industry and the specific application of marine construction as the focus point of this thesis. This is followed by a methodological chapter which explains the development of the central framework employed in this thesis, as well as all its possible applications. Chapter 4 describes the adaption of the presented framework to the case of marine construction including such aspects as overall goal and timeline of analysis, adaption of attributes, as well as the material selection process. Chapter 5 first presents the results for each individual material category and discusses potential improvement options. This is followed by a complete comparison of all analyzed materials and a focus on those developments which may provide the largest long-term benefit for sustainable construction. Finally, Chapter 6 summarizes the insights of this thesis and provides an outlook towards further applications.

2 Megatrends and Floating Infrastructure

The term megatrend was coined by Naisbitt in the 1980s to describe large scale developments in individual, social or technological structures effecting society and economies in the decades to come. He was convinced that in order to predict the future one has to understand the present. Thus, by analyzing current developments and trends a number of larger, more general megatrends could be discerned (*1*). This attempt at predicting future developments has become important for academia as well as industry in order to, for instance, properly prioritize research projects or strategy development. Consequently, there are numerous studies and reports by academics, industry groups and also governments dealing with the topic of trends and megatrends. As there is no clear definition for a megatrend, the use of the term varies from report to report, sometimes seen as mere developments and other times termed as global challenges which will need to be faced in the coming decades.

In the first section of this chapter an in-depth analysis and categorization of existing megatrends is presented. This overview of major long-term developments forms the basis for a logical prediction of future developments that is grounded in scientific data and observations.

In the second section such a prediction is presented. Combining the effects of different megatrends presented in the first section a comprehensive chain of cause and effect surrounding these global developments is constructed. It is then discussed, how the field of marine construction, specifically the concept of floating infrastructure - structures staying afloat due to the buoyancy forces of water - presents a viable approach for addressing these challenges. It is described how through its application to renewable energy generation, food production, flood protection and even urban expansion, floating construction is capable of decoupling multiple linkages in the causal chain. Thus, it can be argued, that there is a significant potential for the marine construction industry to see massive global growth in the coming decades.

The chapter concludes with a section describing the current developments in the field of floating construction and the challenges faced by the industry

2.1 Overview of Existing Megatrends

2.1.1 Different Sources and Categorization of Global Trends and Challenges

One of the largest projects on futures research is the Millennium Project which has released yearly State of The Future reports since its inception in 1996. It is designed as a geographically and institutionally dispersed think-tank with the objective to provide independent, interdisciplinary and multicultural analyses on global long-term opportunities and challenges. For this, 280 international experts from 32 teams contribute to a variety of surveys. The challenges identified in these reports are strongly related to social and humanitarian issues and are shown in Figure 2.1. The State of the Future reports are considered to be the most comprehensive and scientifically accepted compilation of challenges with a global impact and are often used as a basis for deriving other trends having an impact on a selected region or industry (*2*). The Frauenhofer Society for instance compiled a list of challenges in order to direct strategic planning of future research projects (*3*).

Government sponsored reports are another standard source that are published on a regular basis, since governments need to be aware of current developments in order to successfully manage a country's policies and resources. For example, the European Commission released a report in 2009 where global trends are derived from current tensions such as the mismatch between present consumption and the future availability of non-renewable resources. In a second step, the consequences of these trends for the EU member states are analyzed leading to predictions of what would happen if nothing were to change the trajectories of these developments. This allows policy makers to develop laws and regulations to slow down or even prevent certain negative developments or to increase focus on finding specific solutions to critical problems (*4*).

From an industry perspective, there exist reports describing the influence of global trends for almost every industry. The German Association of the Chemical Industry for example published a report in 2013 using global trends to develop scenarios and predictions of what the industry could look like in 2030 (*5*). As mentioned, such reports are available for nearly every conceivable industry for prices ranging from a few hundred to several thousand dollars per report. Identifying global developments and challenges is important for companies, since it allows them to focus early on new potential growth areas and invest in R&D or projects which develop products that may deliver the most promising commercial success in the anticipated markets (*6*).

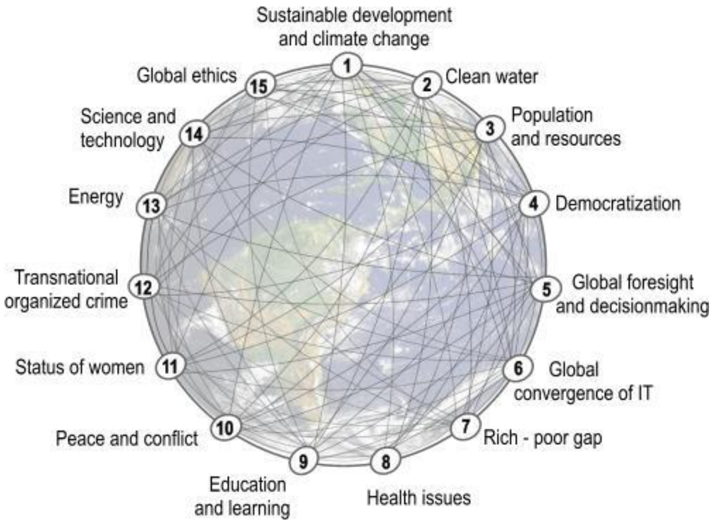

Figure 2.1: Global challenges described in the State of The Future reports (7)

Another view on the different global megatrends of importance can be found in peer reviewed academic journals. The editorial sections of such journals from time to time contain reports written by reputable scientists on the expected future developments of a specific scientific field. Usually these reports are based on the authors' personal experiences and opinions. Although this makes them somewhat biased, they can provide a good inclination of which global developments are important to which fields of science and the research directions experts in the field see as promising.

The sheer number of reports available on possible developments and future scenarios is astonishing and developing a complete overview of global trends is somewhat challenging. When comparing the different sources and viewpoints it becomes apparent that most reports focus on slightly different aspects of basically the same large trends affecting a certain area. These individual trends can be grouped into a number of megatrends, which in turn can be assigned to different categories or areas that are affected by them. All these categories together finally provide an overview of the areas which will change to determine the shape of the world in the future as well as the individual trends that lead to the major developments within these areas. The following classification of trends is deemed practical to develop a detailed overview in the scope of this work but is by no means the only possible way of categorizing the global trends mentioned in the literature. The main categories of trends used for this thesis are social, economic, and political trends as well as trends related to information and technology, energy and resources, and environment and climate change (Figure 2.2). Another category are so-called wild cards. These are unforeseeable events such as major wars, natural disasters or pandemics that have the potential to alter the global status quo suddenly and massively. Since it is impossible to predict the unpredictable this category is not considered any further in this thesis.

The individual trends in each of these areas are numerous and have very different causes and effects. For instance, changing demographics and increasing globalization will strongly affect social life. Economies will be affected by global economic growth and new patterns of consumption, while political changes will stem from a shift in power toward emerging countries such as China and an increase in the global influence of large corporations. Innovations and technological developments will in the next decades be dominated by computing, information and communication technology as well as the convergence of various technological fields. A rising global population will lead to increasing demand not only for food and water but also other resources and energy. Finally, the global climate and environment is strongly affected by continuing global warming but may be stabilized by reductions of greenhouse gas emissions. As this short description shows the main areas are not only affected by individual trends but will also in turn have effects on the development of the other areas. Furthermore, the exact effects on local situations will be different from country to country. Once again as with the trends themselves the nations experiencing these changes can be ordered into larger groups of countries for which trends and developments are forecast to be similar. For the following subchapters, the world is divided into three major groups of countries: The advanced economies (ADV), the emerging economies (EM) and the developing economies (DEV). The ADV group includes the most strongly developed global economies such as USA, Canada, Japan, the EU 27 or Switzerland. The EM group includes countries such as Brazil, Russia, India or China (sometimes also referred to as the BRIC countries). Finally, the DEV group includes the poorest nations mostly located in Africa (Kenya, Ethiopia, etc.) and Southeast Asia (Laos, Vietnam). This grouping does not specifically assign every country to a particular group but is only meant to show which types of countries may expect what kind of developments. It is adapted slightly from a book by Valencia titled: “The Future of the Chemical Industry by 2050” (*8*). In order to provide an overview that is as complete as possible, all identified megatrends and sub-trends will be described in more detail in the following sections.

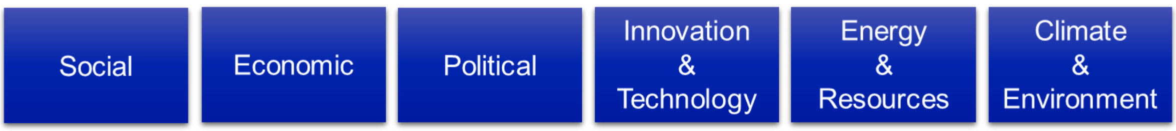

Figure 2.2: Main categories or areas of global megatrends

2.1.2 Social Megatrends

Social megatrends are arguably the most influential of all the megatrend areas. Not only will they significantly determine the future shape of our world, but they drive the development of most other large-scale trends as well. The main trends affecting society as a whole and individual ways of life can be divided into changing demographics, increasing level of globalization, changes in work and education, and changes in social norms and values. Each of these megatrends is influenced by a number of sub-trends as can be seen in the overview in Figure 2.3.

Megatrends	Trends	
Change in Global Demographics	Strong Population Growth (DEV>EM)	
	Low to Negative Population Growth (ADV)	
	Reduction of Global Birthrate	
	Ageing Population (ADV)	
Increasing Globalization	Increasing Global Trade and Mobility	
	Increasing Urbanization (DEV/EM>ADV)	
	Demand Shift Towards Asia	
	Growing Wealth and Middle Class (DEV/EM)	
Changes in Work and Education	Knowledge-Based Society	
	Life Long Learning	
	Interdisciplinary Education	
	Heterogeneous Employee Base	
	Scarcity of Skilled Labor (ADV)	
Changing Norms and Values	Changing Gender Roles	
	Cultural Tensions	

Figure 2.3: Overview of Social megatrends

2.1.2.1 Change in Global Demographics

In line with increasing wealth and knowledge advances in all areas of science, the global population has completed a period of staggering growth in the last 25 years growing from 5.3 billion in 1990 to 7.3 billion in 2015. Alone in 2016 the UN projects another 83 million people will be added to the global population, equivalent to an annual growth rate of 1.1%. As can be seen in Figure 2.4, this level of growth is predicted to decrease slightly throughout the course of the century. Nevertheless, the medium population estimate for 2050 and 2100 are 9.7 and 11.2 billion respectively, leading to enormous pressure on global resources. Consequently, the growing global population is the main driver of developments in the future, since demand for any good, be it food, energy, space or healthcare, scales with the number of existing consumers.

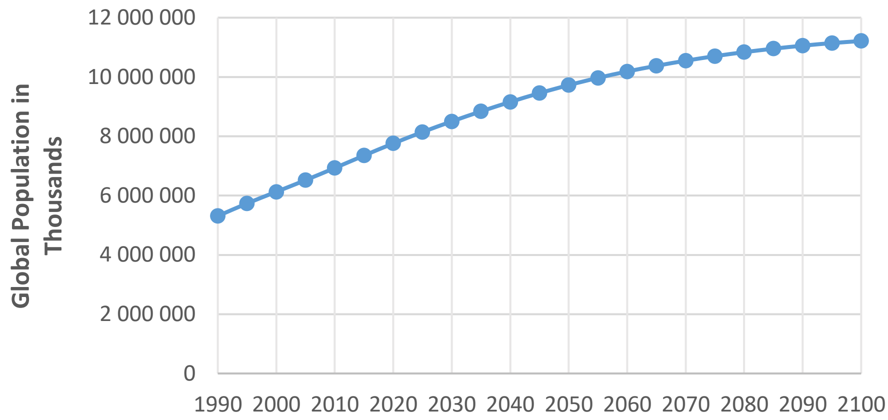

Figure 2.4: Prediction of global population development (9)

A key aspect to consider when speaking of a growing world population is that growth rates have and will continue to vary strongly between different regions. The DEV countries are projected to grow most strongly with annual rates well above 2%. While the EM countries are expected to grow as well with annual rates between 1% and 2% until 2050, most of the ADV countries will be faced with a steady (ex. EU, Switzerland) or slightly declining population (ex. Japan) as a result of the development of a society where low birth rates are common (Figure 2.5). Decreasing birth rates are by no means trends only visible in ADV economies. With levels of wealth and education increasing world-wide, the average global birthrate is predicted to decrease slightly from 2.5 children per woman in 2010-2015 to 2.4 in 2025-2030. The largest decline is expected to take place in the DEV countries with rates decreasing from 4.3 to 3.5 in the same time span. Naturally, the exact predictions are surrounded by a high amount of uncertainty. However, the general trend of an overall declining global birth rate is not controversial (*10*).

Another major trend affecting demographics especially in ADV countries is the increasing life expectancy, which in combination with the mentioned low birth rate will lead to a strongly ageing population. For example, in Europe the percentage of people aged 65 and older is expected to increase by nearly 10% from 2015 – 2050 (*11*). An older population will lead to an increased demand for healthcare and medicine and put high pressure on the individual pension systems, which will require increased spending by governments and individuals to continue functioning. These increasing costs will be a driver for investments in research to develop cheaper, more affordable medicines (*12*). Finally, an ageing population also greatly influences the composition of the workforce leading to a higher percentage of older employees and fewer young professionals. This may require companies to adapt their hiring process and focus more strongly on the strength of the older, more experienced employees who nowadays may have difficulties finding new jobs.

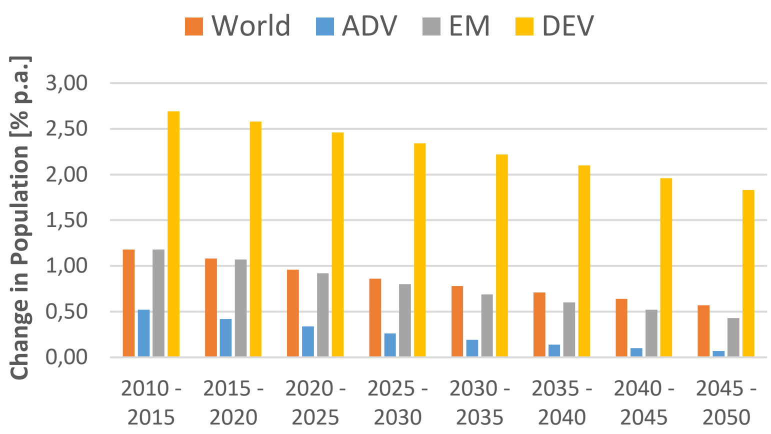

Figure 2.5: Average yearly population growth by region (9)

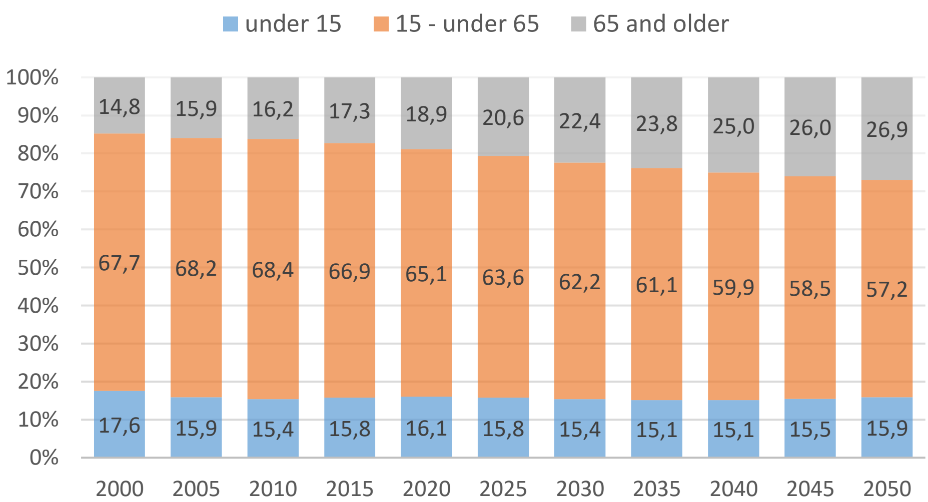

Figure 2.6: Age distribution in Europe in percentage of total population (11)

2.1.2.2 Increasing Globalization

The widespread proliferation of information and communication technologies along with new modes of transport have caused the world to become smaller and smaller. Companies have long since moved from the local level to compete in global markets. This is causing goods and resources to be shipped internationally in ever increasing amounts. In fact, the worldwide exports are expected to triple from 2013 levels until 2030 and their compound annual growth is expected to exceed overall global economic growth in this period (6.9% vs. 6.5% resp.) (*13*). However, this increased level of transport and mobility can also be seen on the individual level. An ever increasing part of the global population will in the future move to live in cities. Urbanization is a trend that can already be observed globally today. The global rate of urbanization is projected to increase from 54% in 2014 to 66% by 2050. In combination with ongoing population growth this is equivalent to 2.5 billion people being added to the world's urban population. Cities will have to grow to accommodate this huge amount of people leading to high demand for construction materials and real estate. On the other hand, continuing growth will present significant challenges related to environmental, health, logistical and also cultural issues. These challenges will be especially prevalent for the increasing number of so-called megacities – cities with more than 10 million inhabitants. In 2014 there were 28 megacities world-wide, Tokyo being the largest with slightly less than 38 million inhabitants (Figure 2.7). Of these cities only 7 were located in ADV countries, 14 in EM countries and 8 in DEV countries. By 2030 12 more cities will grow to exceed the 10 million mark. Following the developments of population growth the rate of urbanization is predicted to increase more strongly for EM and DEV countries concentrated mainly in African countries, India and China (*14*).

Another important aspect of globalization is the rising importance of Asian markets due to economic development and population growth. By 2025 China could become the second largest global market behind the US, and India could surpass countries like France or Italy (*4*). This growth will shift not only global demand but also production capacity. With increased demand and production the Asian countries will achieve new levels of wealth which will lead to the development of a steadily expanding middle class. An expansion of the middle class will in turn lead to increasing demand for leisure, as well as luxury and lifestyle products providing overwhelming economic opportunities to domestic and foreign companies. However, not only wealth and the demand for goods will increase in these regions. The people may also strive for a stronger political voice, which may lead to tensions in some countries.

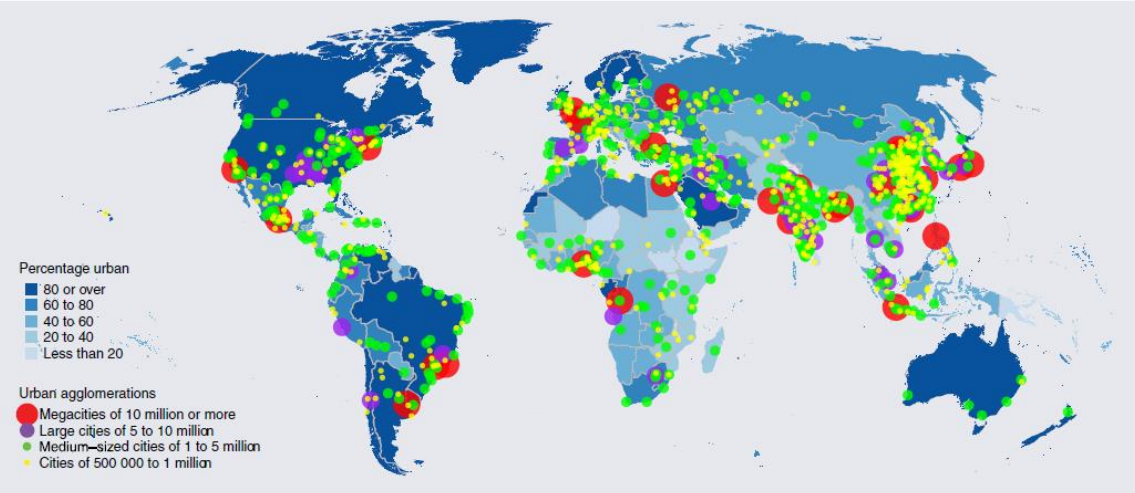

Figure 2.7: Percentage urban and location of urban agglomerations with at least 500,000 inhabitants, 2014 (14)

2.1.2.3 Changes in Work and Education

With increasing technological development, the world is moving further and further towards a knowledge-based society. Intangible assets such as intellectual property and human capital will predominantly determine who comes out on top in globally competitive markets with emerging knowledge-based technologies disrupting traditional markets. Since companies will rely more strongly than ever on the knowledge of their employees, the quality of local educational systems will become an important location factor. Along with the rising importance of education will come changes in the way of working, which will be especially prevalent in the ADV and also the EM countries. Since knowledge is the critical resource of the coming decades, employees will need to focus on constantly developing their knowledge base leading to a system of lifelong learning. The individual of the future can be seen as an entrepreneur adapting his skill set to best meet the rapidly changing challenges facing the world around him (*2*, *5*).

Next to changing importance of education there will also be a change in the way people are educated. The increasing complexity of technologies and markets calls for interdisciplinary studies combining different traditional fields to provide students with a more appropriate toolkit. The increasing diversity of study programs will lead to a highly heterogeneous employee base from which employers will be able to choose the most qualified for increasingly specific positions or tasks (*12*). Nevertheless, with an ageing and shrinking population companies in ADV countries are in danger of experiencing a shortage of skilled labor which could greatly limit their technological potential. Consequently, the global competition for talent will increase and countries having liberal immigration laws may be able to profit from the high mobility of qualified individuals. Therefore, this is a trend that can be mitigated or exacerbated by governmental policy making (*5*).

2.1.2.4 Changing Norms and Values

As society grows, technology advances, and the world becomes smaller, social norms and values will adapt to the new realities. This adaption is accelerated by the increased interactions between culturally diverse individuals. This will require a willingness for change from all individuals, as well as governments, which will take time to develop. Until then, increasing intercultural interaction between people with a fixed mind-set will also lead to increased tensions and maybe even conflict. An important example for evolving social norms is the change in gender roles with increasing importance and empowerment of women around the globe. For instance, the percentage of women in parliaments has increased twofold in the last 20 years from 11% to 22%. Despite many positive developments, violence and discrimination towards women is prevalent in many parts of the world and it will require radical changes in local values before they can be abolished (*15*).

2.1.3 Economic Megatrends

The second major driver of global changes in the next decade is the group of megatrends that are related to the development of the global economy as a whole and discrepancies between individual national economies. This area can be divided into three megatrends: Global economic growth, new patterns of consumption and consolidation of national finances (Figure 2.8).

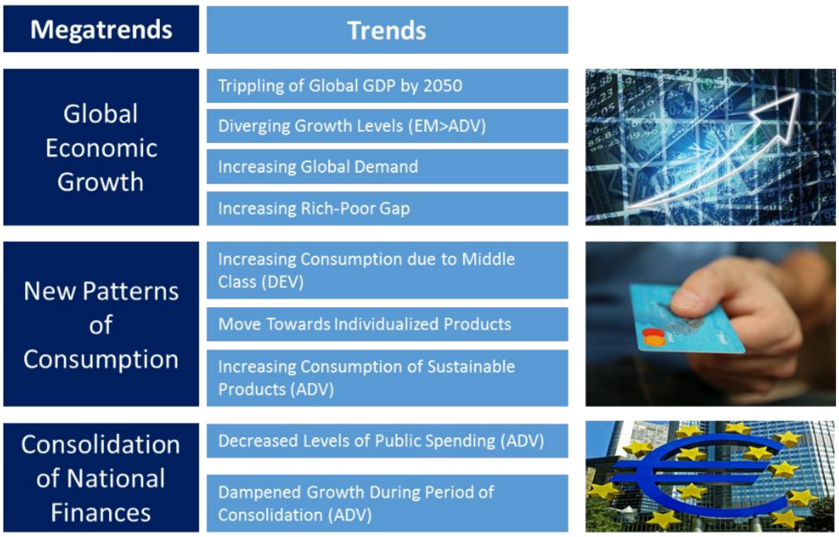

Figure 2.8: Overview of Economic megatrends

2.1.3.1 Global Economic Growth

With global population growth remaining at relatively high levels, global demand and consequently supply is predicted to increase substantially as well in the next decades. In terms of global GDP, world-wide economic output is expected to double from 78 trillion $ in 2014 until 2037 and nearly triple until the year 2050. This amounts to a global compound annual growth rate of slightly over 3%. When looking at the growth rates of the individual economies, there is a clear difference between those of ADV countries (2.1% p.a.) and of EM countries (3.8% p.a.) (*16*). This two-speed economy will continue to shift the distribution of global GDP and also the global power balance towards the EM countries especially those located in Asia (*17*). To exemplify: In 2014 China has already surpassed the US as the largest economy at purchasing power parity (PPP) exchange rates. According to projections by PWC, India is to overtake the US as well by 2050, becoming the second largest economy in the world followed by the US (and the EU-27 if counted as a single economy). These three global powers will account for almost 50% of global GDP and individually outperform the following four most productive economies combined (Indonesia, Brazil, Mexico and Japan). An exact overview of these projected developments is given in Figure 2.9 (*16*). Naturally, these projections are once again highly unsure and rankings vary from source to source. For instance, the Economist calculates that the US will remain the second strongest economic power throughout 2050 followed by India, Indonesia and Japan (*18*). Despite these differences the overall trends remain the same.

Although it is predicted to be extremely high for a number of countries in the short term, the level of economic growth will decrease and revert towards the global average in the long term, as these countries' economies move closer to the state of the ADV economies (Figure 2.10). Furthermore the higher growth levels of the EM countries will still not be enough to close the wealth gap with the ADV countries, whose GDP per capita will remain around twice as high as that of the EM and three times as high as that of the DEV countries (*8*).

	2014		2030		2050	
PPP rank	Country	GDP at PPP (2014 US$bn)	Country	Projected GDP at PPP (2014 US$bn)	Country	Projected GDP at PPP (2014 US$bn)
1	China	17,632	China	36,112	China	61,079
2	United States	17,416	United States	25,451	India	42,205
3	India	7,277	India	17,138	United States	41,384
4	Japan	4,788	Japan	6,006	Indonesia	12,210
5	Germany	3,621	Indonesia	5,486	Brazil	9,164
6	Russia	3,559	Brazil	4,996	Mexico	8,014
7	Brazil	3,073	Russia	4,854	Japan	7,914
8	France	2,587	Germany	4,590	Russia	7,575
9	Indonesia	2,554	Mexico	3,985	Nigeria	7,345
10	United Kingdom	2,435	United Kingdom	3,586	Germany	6,338
11	Mexico	2,143	France	3,418	United Kingdom	5,744
12	Italy	2,066	Saudi Arabia	3,212	Saudi Arabia	5,488
13	South Korea	1,790	South Korea	2,818	France	5,207
14	Saudi Arabia	1,652	Turkey	2,714	Turkey	5,102
15	Canada	1,579	Italy	2,591	Pakistan	4,253
16	Spain	1,534	Nigeria	2,566	Egypt	4,239
17	Turkey	1,512	Canada	2,219	South Korea	4,142
18	Iran	1,284	Spain	2,175	Italy	3,617
19	Australia	1,100	Iran	1,914	Canada	3,583
20	Nigeria	1,058	Egypt	1,854	Philippines	3,516
21	Thailand	990	Thailand	1,847	Thailand	3,510
22	Egypt	945	Pakistan	1,832	Vietnam	3,430
23	Poland	941	Australia	1,707	Bangladesh	3,367
24	Argentina	927	Malaysia	1,554	Malaysia	3,327
25	Pakistan	884	Poland	1,515	Iran	3,224
26	Netherlands	798	Philippines	1,508	Spain	3,099
27	Malaysia	747	Argentina	1,362	South Africa	3,026
28	Philippines	695	Vietnam	1,313	Australia	2,903
29	South Africa	683	Bangladesh	1,291	Colombia	2,785
30	Colombia	642	Colombia	1,255	Argentina	2,455
31	Bangladesh	536	South Africa	1,249	Poland	2,422
32	Vietnam	509	Netherlands	1,066	Netherlands	1,581

Figure 2.9: Projected development of global GDP ranking (16)

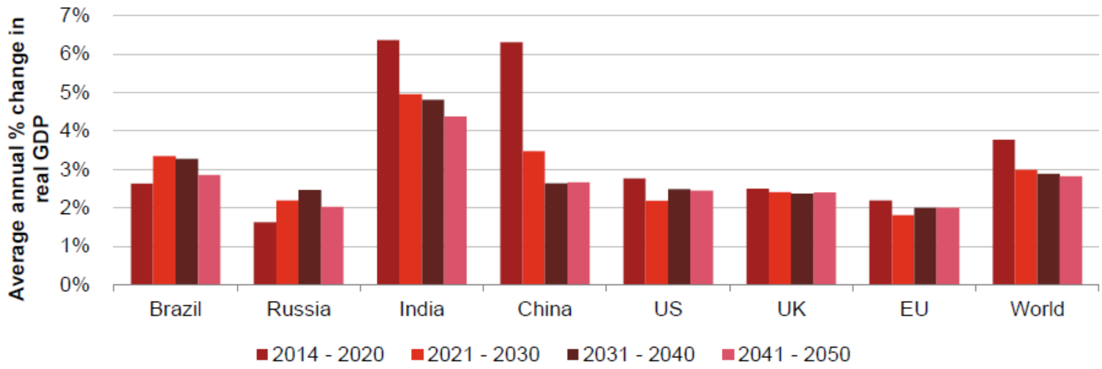

Figure 2.10: Projected growth paths for selected economies (16)

2.1.3.2 New Patterns of Consumption

Accompanying changes in society and economic developments are changes in consumer behavior and thus consumption patterns. Depending on the level of a country's development, these changes will once again vary greatly. As the global economy grows the DEV and EM countries will be able to participate in the created wealth. The advances in these countries towards fully industrialized economies will give rise to an increasing number of people with higher income levels. This growing middle and upper class will demonstrate its newly acquired wealth through consumption, significantly increasing demand for a wide array of products ranging from commodities to luxury goods. In the ADV countries on the other hand there will be an increasing focus on individualized products ranging from customizable consumer products through personalized medicine to fully developed business solutions. Furthermore, consumers are more and more aware of the environmental impacts of their decisions and many have the desire to live in a more sustainable manner. This increasing level of environmental awareness will drive demand for sustainable products promising to enable a healthy lifestyle (*6*).

2.1.3.3 Consolidation of National finances

The economic growth of many ADV countries over the past decades was financed substantially by public and private debt. In light of the record levels of debt that have been reached, continued growth of these economies along this path is not possible. Consequently, many European countries as well as the US have already begun consolidating their national finances. Especially European countries which received financial support from the European Stability Mechanism or the International Monetary Fund in the past are faced with strong pressure to decrease public spending and consolidate debt. Due to these developments the global level of public debt is expected to decrease over the next decades (Figure 2.11). Increased interest rates for highly indebted countries along with decreases in public spending will dampen economic growth and, in an effort to maintain political stability, lengthen the period of consolidation for many countries. Along with shrinking populations and limited possibilities for expansion these forced but nevertheless necessary cuts in public spending are also responsible for the diverging levels of growth between the ADV and EM economies (*5*).

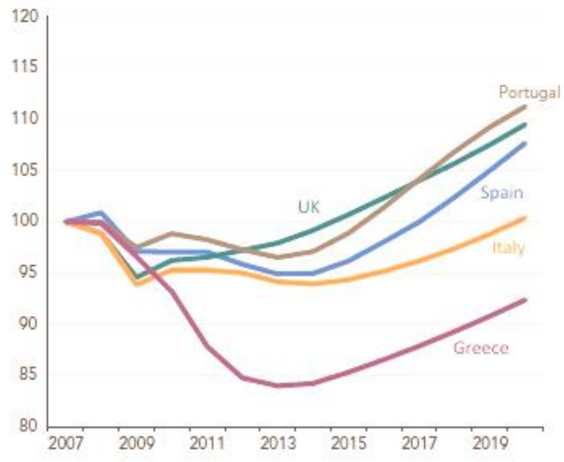

Figure 2.11: Development of GDP in selected European countries (Index 2007 = 100, adapted from (5))

2.1.4 Political Megatrends

Global trends effecting populations and economies will be accompanied by changes in the global political environment which will also be driven to a large part by technological developments in the area of social networks and the internet. The major political trends identified are the move towards a new world order, the emergence of mega-corporations, an increasingly important role of governments, and globally increasing tensions and threats. An overview of political megatrends and trends is given in Figure 2.12.

Figure 2.12: Overview of political megatrends

2.1.4.1 New World Order

Political leadership has been far from stable in the last century with periods of minor gradual changes as well as events triggering major reorganizations of the global political landscape and business environments. The two world wars are examples of such major events. Since the Second World War, step wise changes have given way to more constant and persistent reformation of world order (*19*). In the past decades, this reformation has been a consequence of the increasing populations and economic outputs of the EM countries. The transition of global demand and production towards these countries will continue in the future and will be accompanied by a shift in political influence and power away from the DEV nations. Specifically, China and India will become global powers mainly at the expense of the United States and to a certain extent also Europe, thus moving the political landscape further and further towards a truly multipolar world.

The redistribution of international power will also have major consequences for existing international organizations. These organizations still mostly reflect the global power distributions from the time of their inception, i.e. shortly after the Second World War, as is evident when looking at facts such as headquarter locations, votes, veto powers, presidents etc. Organizations such as the UN, the World Bank, the IMF or even the OECD will have to adapt and reorganize to better reflect the new status quo. In addition, new international organizations will need to be formed to address novel international co-operations or political tensions (*8*).

Next to the power shift between countries there is also a trend related to the shift of power within countries. The emergence and global proliferation of the internet and to an even larger extent social networks has allowed individuals from around the world to connect with each other and exchange values, views and ideas with increasing ease. These means of connection significantly increase the power of individual citizens as they can easily find people of a similar mind-set and organize themselves to work jointly against larger entities such as governments or companies. With growing possibilities, people from around the world will push towards greater political determination rights. Developments like these may not only help to accelerate the process of global democratization, but have the potential to greatly destabilize the nations in which such transitions occur. The potential danger radical political changes leading to power vacuums present is clearly depicted by the events that occurred following the Arab spring (*8*).

2.1.4.2 Emergence and Increasing Power of Mega-Corporations

Accelerated economic growth and an ever-increasing globalization has led to never before seen levels of international competition. To remain competitive in global markets, companies have been forced to take all possible measures to continue growing. Consequently, the growth of such companies fueled by international acquisitions and expansions has created so-called mega-corporations – corporations that grow faster and produce more revenues than individual countries. The sheer size of these corporate entities becomes evident when looking at the top 100 economies of the world in 2014, 63 of which are companies (Figure 2.13). Naturally, this tremendous size gives mega-corporations a high level of influence over local economies which increases their exposure to governments and citizens. Consequently, these companies will have a higher level of responsibility when it comes to issues such as social welfare, transparency, sustainability and governance. Furthermore, once again fueled by the development of social networks, reputation and accountability towards society will become more and more critical.

Government/ Corporation	2014 Revenues, Billions US $	Government/ Corporation	2014 Revenues, Billions US $	Government/ Corporation	2014 Revenues, Billions US $
United States	3,029	Berkshire Hathaway	195	Allianz	128
China	2,285	Denmark	193	Verizon	127
Germany	1,680	Chevron	192	Kuwait	125
Japan	1,512	Turkey	190	BNP Paribas	125
France	1,507	India	186	AmerisourceBergen	124
Italy	991	McKesson	174	Fannie Mae	122
United Kingdom	936	Daimler	172	LukOil	121
Brazil	861	ICBC	167	Bank of China	121
Canada	675	EXOR	158	Greece	120
Spain	530	Gazprom	158	Honda Motor	117
Australia	493	General Motors	156	Argentina	117
Wal-Mart Stores	486	AXA Group	154	Costco Wholesale	116
Sinopec	428	Phillips 66	150	Colombia	114
Royal Dutch Shell	420	General Electric	149	General Group	112
Russia	417	E.ON	148	JX Holdings	111
Netherlands	414	Finland	146	Hewlett-Packard	110
Exxon Mobil	376	Eni	146	Kroger	109
BP	353	Ford Motor	144	JP Morgan Chase	102
South Korea	351	Petrobras	144	Iraq	101
State Grid	334	Venezuala	143	Express Scripts Holding	101
PetroChina	333	United Arab Emirates	141	Portugal	100
Mexico	301	China State Construction Bank	140	Nestle	100
Norway	294	CVS Caremark	139	Bank of America	95
Sweden	291	Hon Hai Precision	139	IBM	94
Saudi Arabia	279	Indonesia	135	Poland	93
Volkswagen Group	269	AT&T	132	Marathon Petroleum	91
Belgium	268	Valero Energy	131	Cardinal Health	91
Toyota Motor	252	UnitedHealth Group	131	Citigroup	91
Switzerland	228	China Construction Bank	131	Boeing	90
Glencore International	221	Agricultural Bank of China	129	Amazon	89
Austria	218	Rosneft	129	Wells Fargo	88
Total	211			South Africa	87
Apple	199			Microsoft	87
Samsung Electronics	196				

Figure 2.13: Global top 100 economies 2014; Sources: Companies – Forbes, Countries – IMF (20)

2.1.4.3 Increasing Role of Governments

Governments have traditionally had a rather important role for their societies and economies. In the past decades, government spending accounted on average for 15-20% of total GDP in ADV and EM countries. During the financial crisis of 2008 governments were forced to inject billions into their economies in the form of stimulus packages or bailouts of failing companies to keep the entire system from collapsing. In the most extreme case of Saudi Arabia these stimulus packages alone accounted for around 26% of total GDP in 2009. In other countries the extent of the stimulus packages was smaller, but still significant, reaching around 6% (Russia, USA) or 3% of total GDP (Japan, EU, Brazil, Canada). This increased influence is expected to continue and the role of government as the economies largest single customer will remain unchanged. Additionally, there will need to be an entity that can match the power of the emerging mega-corporations. Hence, a key role of governments will be increased monitoring of corporations in order to ensure compliance with laws and regulations put in place to protect the individual citizen. On the other hand, regulations made without clear scientific and economic knowledge may hinder positive developments and innovation in individual countries causing them to loose competitive advantage on the global scale (*8*).

2.1.4.4 Increasing Tensions and Threats

Increasing globalization and internationalization has allowed diverse cultures around the globe to come into contact with each other. While this has many positive aspects, it has also led to ever increasing cultural clashes, especially when traditional ways of life are threatened to be changed by outside forces. The negative consequences of outside intervention in politically instable regions are exemplified by the growing threat of terrorism throughout the past two decades. 8441 terrorism related incidents were counted in 2012 and more than 5000 occurred in the first half of 2013 alone. One of the largest threats is so-called lone wolf terrorism, where an individual acts on his own and with his own intentions. Anticipating or discovering such a threat is extremely difficult even with highly sophisticated surveillance technology.

Technological developments such as the internet, next to all their indisputable advantages, have also opened the door for new dimensions of organized crime and industrial espionage. For example, Akamai Technologies, an American content delivery network and cloud services provider, estimates that on July 24th 2013 there were 628 cyber-attacks in a time span of only 24 hours, the majority of which targeted US based computers (*21*). Consequently, cyber security has turned into an intellectual arms race between hackers and security providers developing new and improved defense strategies for governments and corporations (*22*). All these destabilizing forces will continue to drive the need for security and protective solutions around the world leading to further technological developments with positive as well as negative effects on global security.

2.1.5 Innovation and Technology Megatrends

Technological advances and breakthrough innovations have always been a significant driver of change affecting almost every aspect of life in modern societies. In order to overcome the immense challenges facing mankind today, technology will be one of, if not the most important part of the solution. Not only do innovations lead to changes in society, but also the way in which research is done and technologies develop has changed significantly over the years. Individual researchers working on their own in small laboratories have connected with others to form huge multinational collaborations of scientists attempting to solve ever grander challenges. In this section the main megatrend related to the way innovations are predicted to arise in the future, known as technological conversion, is presented. After this, future developments in the research area of computing and information and communication technology (ICT), which significantly drives innovations in other fields, are described. Figure 2.14 provides on overview of these trends.

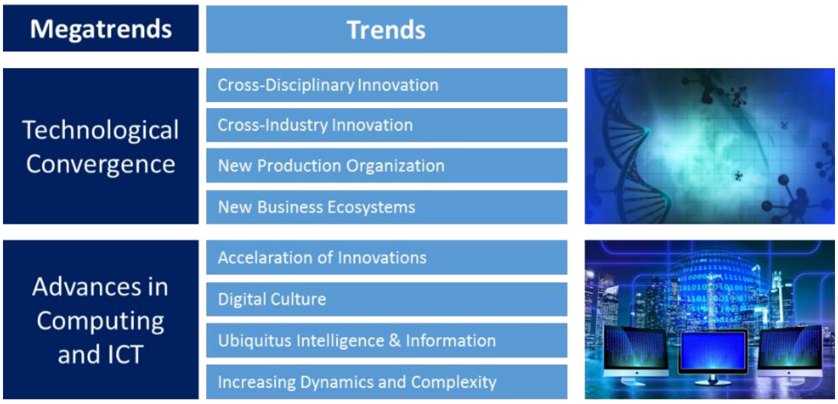

Figure 2.14: Overview of Innovation & Technology megatrends

2.1.5.1 Technological Convergence

Due to the sheer size of the grand challenges humanity as a whole is facing at the moment, it is clear that a satisfying solution cannot be produced by experts of one single scientific discipline alone but requires innovations from a wide variety of fields. In fact, most true modern scientific breakthroughs are no longer made within traditional disciplines but at the interface between them, thus giving rise to new interdisciplinary fields of research. Examples of such converging fields are biochemistry (which has spread even further to for instance physical biochemistry or computational biochemistry), chemical engineering, nanoelectronics or photonics (*6*, *23*).

A consequence of this blurring of disciplines is that not only academia but also industry has long since begun to move outside of its traditional sectors to produce cross-industry innovations such as electric vehicles, which required input from automotive, electronics and chemical companies. In fact, the increasing competitiveness of global markets has forced companies to stretch out along the value chain and work more closely with suppliers and customers to produce innovative products in order to survive. This new way of innovation has and will continue to change the way a successful production organization looks like, increasing communication between players, and cementing the dominating importance of business networks and collaboration (*2*).

2.1.5.2 Advances in Computing and ICT

The one technology that has changed society the most in the past decades is clearly the development of the personal computer and the internet. These innovations have enabled a multitude of breakthroughs in nearly all major fields of science and will continue to accelerate innovation across disciplines in the future. Computers and the internet have become so prominent in our daily life that society as we know it would not be able to function without it. More and more devices are connected to the internet. The development of the so-called “internet of things” is a further step in the move towards a digital culture. In this digital culture information is a key resource and is available at the push of button. In fact, the amount of information that can be accessed by any single person is so huge that managing this information and discerning the relevant from the irrelevant is becoming increasingly difficult and requires a certain amount of experience and skill. Data management will therefore become more and more central to any type of organization. Sometimes referred to as “dynaxity” the increasing dynamics and complexity of daily life and also business is driven mainly by the proliferation of digital technologies and exponential growth of computing power (*2*).

2.1.6 Energy & Resource Megatrends

Arguably the biggest challenge of the next decades is to generate enough resources to sustain a dramatically increasing global population as well as provide enough energy to enable the predicted levels of economic growth around the globe and to do this in an environmentally friendly and sustainable manner. The trends in the area of energy and resources all deal with increasing demand and the consequent supply issues. The main areas of interest are food and water as well as energy (Figure 2.15).

Figure 2.15: Overview of Energy & Resource megatrends

2.1.6.1 Growing Demand for Food and Water

Global population and economic growth goes hand in hand with strongly rising demand for resources. The most basic resources required for human survival are food and clean water. Despite the staggering growth in population, the global society has made great advances in the past when it comes to combating hunger. The percentage of global population suffering from undernourishment has been decreased from 18.6% in 1990 to 10.8% in 2014, a decrease of 218 Million people. Nevertheless, there are still 768 Million people worldwide that cannot get access to sufficient amounts of food and inequality in distribution of global food production is still an issue (*24*). Estimates on the increase in global demand for crops from 2005 to 2050 range from 70% (*25*) to 100% (*26*). This demand increase is not driven solely by population growth. There is a clear correlation between the wealth of a nation and the calorie consumption per capita per day of its population as can be seen in Figure 2.16. Therefore, increasing wealth in EM and DEV countries will further drive the demand for food. Additionally, an increase in wealth will lead to a shift towards a more protein heavy diet and thus to a striking increase in the demand for meat (*26*). Since animal-based food requires almost 5 times more space per nutritional value than plant based food, this development consequently exacerbates another problem facing agricultural production in the future, namely space (*27*). Roeffen et. al. estimated that in the conservative scenario 6 million km^2 of additional land will be required for agriculture by 2050 (*28*). With growing population, industrial production and rising levels of urbanization space use conflicts between housing, agriculture and industry will thus need to be solved in the future.

Feeding the global population is not only a matter of supply but also price. Fueled by the increase in demand, global trade and sadly also speculation, global food prices have more than doubled since the 1990s. According to Oxfam this development is expected to continue with price increases of up to 180% expected until 2030 (*29*).

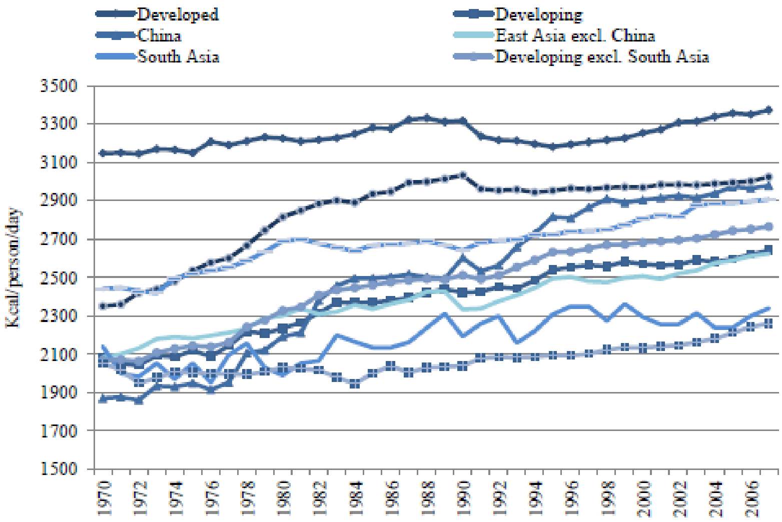

Figure 2.16: kcal/person/day, by region and country groups, 1990-2007 (25)

Agricultural production is not possible without the input of energy and other resources which are vital for human survival, especially water. The agricultural sector is by far the largest user of freshwater accounting for 67% of global demand in 2013. Although this percentage is expected to decrease due to technological advances until 2050 (Figure 2.17) it will still remain the largest single consumer with 37% of total consumption thus putting additional pressure on the already precarious situation of freshwater security (*27*). Once again despite significant advances in the past with 2.3 billion people receiving access to safe drinking water since 1990, water tables around the world are falling and people who currently have access to clean water may no longer have it in the future. The OECD estimates that by 2030 half the people around the globe could be living in areas affected by severe water stresses. As Figure 2.18 depicts there are many countries around the world, mainly in Africa and Asia, but also Europe that already today are affected by fresh water shortages.

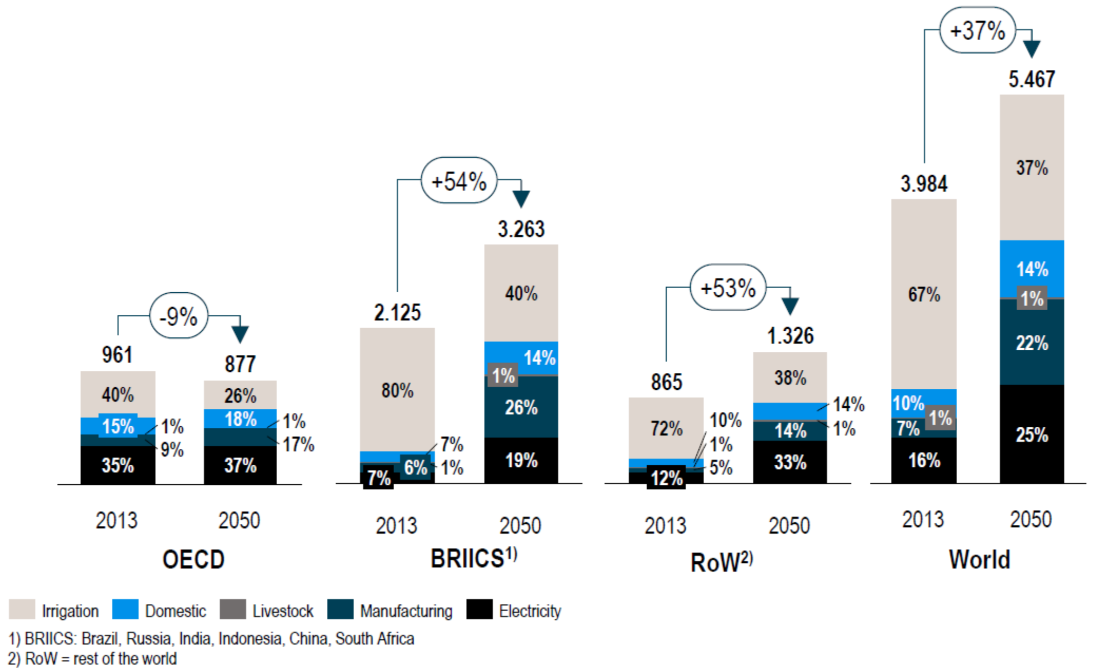

Figure 2.17: Global water demand 2013 vs 2050 in km³ (27)

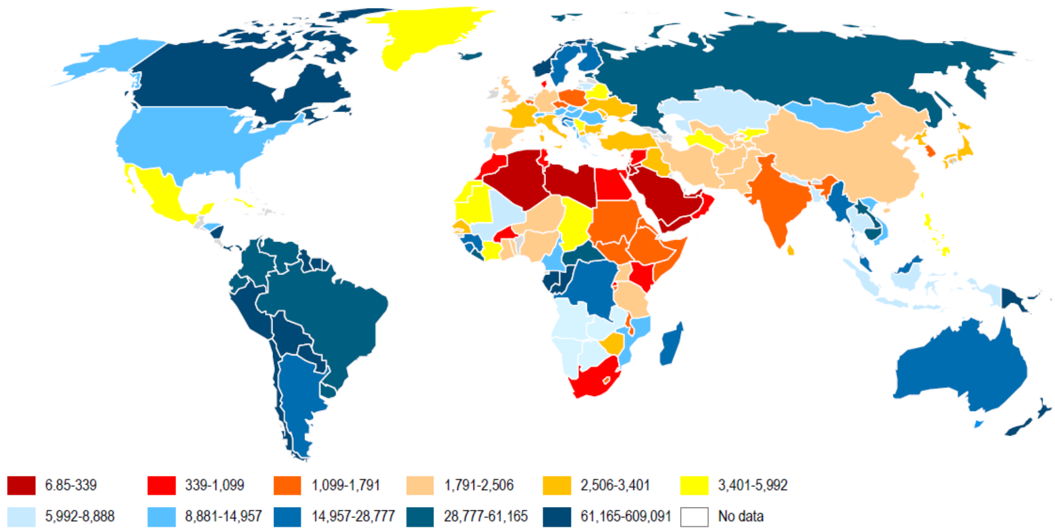

Figure 2.18: Total renewable water resources per capita in 2008 by country in m³/inhabitant/year (27)

To meet these increasing levels of demand for food and water in a sustainable and affordable manner a more efficient use of resources is required in the future. This can be achieved in one of two ways. The first is increasing efficiency of agricultural and industrial production to minimize the use of resource inputs for a given output. The second is minimizing waste. The predominant way of increasing agricultural efficiency in the past has been the development of fertilizers and crop protection chemicals. Developments in these areas will continue, however the potential for further improvement is thought to be rather low. Another area which is gaining traction is the development of genetically modified organism (GMOs). Through this genetic modification it is possible to breed crops that require less resources to grow, can be immune to certain chemicals or pests and provide superior nutritional values than conventional plants. Despite these advantages GMOs are controversial due to concerns about their effects on the natural environment and the business model GMO producers have put in place, with farmers being required to buy new seeds every year and paying high licensing fees for using them.

Concerning the minimization of waste there exists a huge potential for improvement. In 2011 the FAO estimated that roughly one third of global food production was wasted or lost throughout the supply chain from agricultural production to household consumption amounting to a staggering 1.3 billion tons of food waste (*30*). Concerning food, the minimization of waste is to a large extent a social issue, where especially individuals in ADV and EM countries will need to be educated in order to change their consumption habits. Next to a minimization of waste along the supply chain - for food as well as for other resources - the development and implementation of recycling technologies and processes is paramount if supply shortages are to be avoided in the future. The main driver for increased levels of recycling are regulations that have been put in place by governments forcing corporations and consumers to deal with industrial waste appropriately. The European Commission for instance has set clear targets for banning landfilling and is aiming to reach a recycling target of 70% by 2030 (49% in 2010) (*27*).

2.1.6.2 Increasing Energy & Fuel Demand

Energy has always been and will continue to be a key enabler and also a requirement for economic growth. Consequently, the demand for energy will increase dramatically in the future especially in the rapidly growing EM countries. The International Energy Association (IEA) estimates that global energy use will increase by one third from 2015 to 2040. As is displayed in Figure 2.19 the majority of today’s energy is supplied by fossil fuels dominated by oil and coal but also to a growing extent natural gas. An issue with global energy reserves is that they are unevenly distributed, and locations of supply and demand do not match. Consequently, the world is divided into a number of energy exporting countries such as the UAE, Saudi Arabia or Russia and major importers of energy, for instance the EU countries. Investments in renewables and nuclear energy have the potential to decrease the dependency of importing countries as well as limiting global carbon emissions. In the following the projections for each energy source will be looked at in greater detail. The reduction of carbon emissions from energy generation in order to combat global warming can also be seen as a trend in the area of energy generation. In this overview however it was decided to include it in the next chapter focusing on environmental and climate related megatrends.

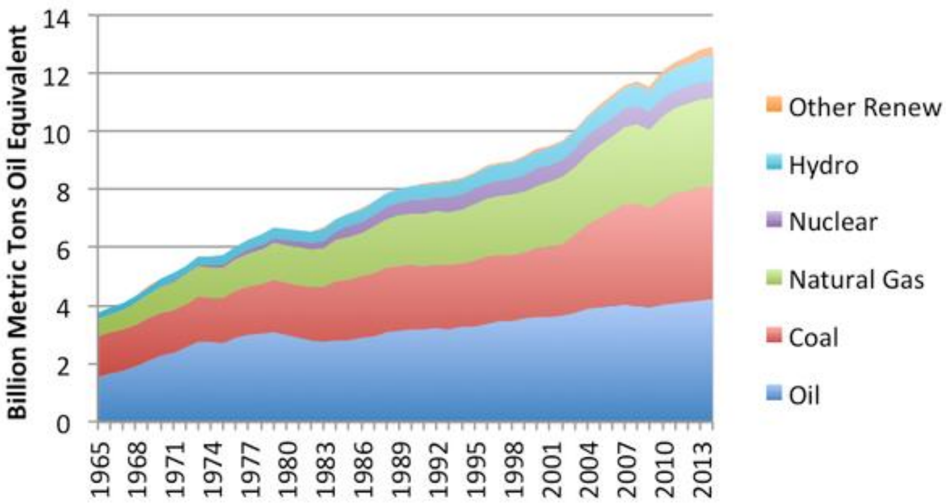

Figure 2.19: Global energy consumption by fuel type (31)

2.1.6.2.1 Oil

Global demand for oil is projected to rise from 88 million barrels a day in 2010 to 103 million barrels a day in 2040. The largest increase in demand will stem from China which may shift its energy production, which is currently focused strongly on coal, towards oil and gas in the future. In contrast to the EM countries oil demand is expected to collectively drop in the US, EU and Japan by 10 million barrels a day by 2040 as these countries shift their energy mix further towards renewable and nuclear power (*32*). In light of increasing demand there have long since been discussions on when global oil reserves will run out. The most famous prediction was made by M. King Hubbert, who argued in 1956 that the world would reach a peak in oil production around the year 2010 at a level of 80 million barrels a day. As was shown before the world has surpassed this peak. Over time more and more reserves were discovered through more detailed and sophisticated geological surveys and new technological developments enabled access to more difficult to reach sources such as oil from the deep sea. The main issue concerning oil supply in the future are consequently the widely different refining costs for different sources of crude oil (Figure 2.20). Oil from conventional onshore sources has rather cheap production costs. Once demand exceeds the supply of these sources production costs for further supply will increase dramatically leading to higher prices. So at least for the next decades the question is not if there is enough oil to meet demand, but whether the price of oil will remain economically feasible for producers as well as consumers (*8*).

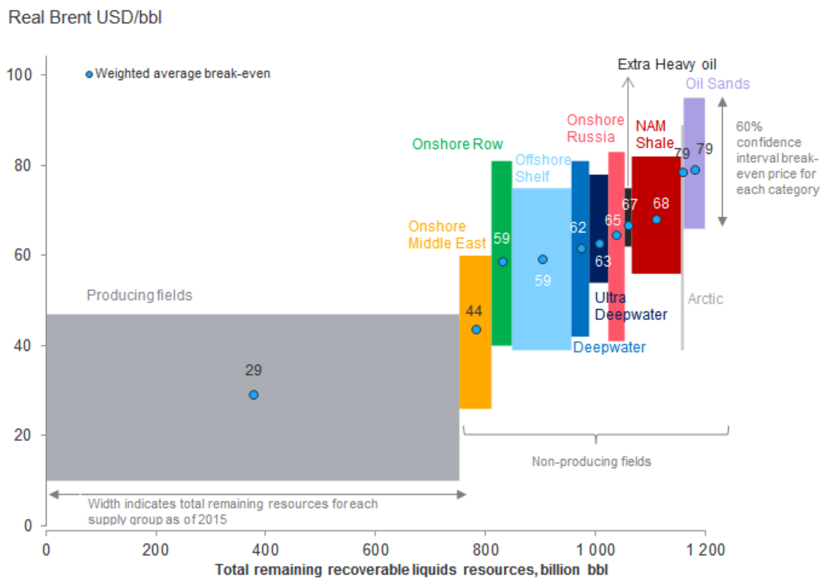

Figure 2.20: Cost curve of global liquids resources (The break-even price is the Brent oil price at which NPV equals zero using a real discount rate of 7.5%) (33)

2.1.6.2.2 Coal

From 2000 to 2009 the share of coal in the global energy mix has increased from 23% to 29%. This fraction is expected to decline strongly in the coming decades mainly due to more stringent regulations aimed at mitigating carbon emissions and global warming. Demand for coal may however remain high in Asia with projections estimating that by 2040 this region will account for four out of every 5 tons of coal consumed globally (*32*).

2.1.6.2.3 Natural Gas

Natural gas is the fastest growing of the fossil fuels. This is mainly due to its low price and lower carbon emissions than gas or coal allowing it to replace these sources in the energy mix especially for countries that have implemented emission policies. Natural gas production is expected to increase by an astounding 50% until 2040 partly to meet new demand and partly replacing more carbon intensive energy sources. The recent discovery of shale gas for instance in the US has doubled the estimated global reserves of natural gas and also geographically spread the availability of this resource increasing energy supply security for many countries. The use of shale gas and other so-called unconventional gas is expected to increase from 17% of total output in 2014 to 31% in 2040. Despite the high availability and relatively cheap production cost a major issue concerning shale gas is the extraction technique known as fracking which is environmentally highly controversial and may thus limit the potential of these newly discovered reserves (*8, 32*).

2.1.6.2.4 Renewables

While the prices of fossil fuels are expected to increase due to increasing extraction costs, the opposite is true for renewable energies. Following further technological developments cost reductions are currently the norm for energy generated from renewable sources. Next to the decreasing price levels the goal of meeting the future energy demand in a sustainable and safe way will serve to drastically increase global energy production from renewable sources such as solar, wind or hydro. The IEA estimates that energy from renewable sources will reach a share of over 25% in the USA, 30% in Japan and China and even 50% in the European Union by 2040 (*32*). The role renewable energies will play to limit carbon emissions in the light of global warming will be covered in more detail in the next subchapter on Environmental Megatrends.

2.1.6.2.5 Nuclear

Finally, nuclear energy as a highly efficient and carbon neutral power source is facing an uncertain future. Since the tragic events in Fukushima following a major earthquake in March 2011 a new debate has been triggered about the safety, value and sustainability of this power source. Some countries such as Germany and Switzerland have gone as far as to politically commit themselves to completely phase out nuclear power until 2020 and 2034, respectively. The retirement of older nuclear reactors around the world is estimated to cost around $100 billion. Despite these developments nuclear power generation capacity is expected to increase by 60% until 2040 mainly due to new reactors being installed in China, India, Korea and Russia. The main reason is that nuclear power provides a high supply security for producing countries and also adds stability to electricity costs. Furthermore, as already mentioned nuclear power is to date one of the only options available at a sufficient scale to reduce carbon emissions without jeopardizing supply security. Nevertheless, the storage and disposal of radioactive waste is still an unsolved issue and will need to be addressed with high priority by countries currently operating or planning to operate nuclear power plants (*8, 34*).

2.1.7 Climate & Environmental Megatrends

In the last 45 years the globally economy increased more than fivefold bringing with it improved living standards and a better quality of life in many areas of the world. Unfortunately, the simultaneous increase in demand for energy of nearly 220% brought with it an increase in global CO_2 emissions of 182% giving rise to the first truly global great challenge, climate change. In this chapter the megatrends concerning the consequences of global climate change are reviewed along with trends concerning sustainable and responsible treatment of the natural environment. The megatrends which are looked at are global warming, the reduction of greenhouse gas emissions (esp. CO_2), the move towards more carbon-efficient processes and technologies as well as the increased importance of environmental security (Figure 2.21).

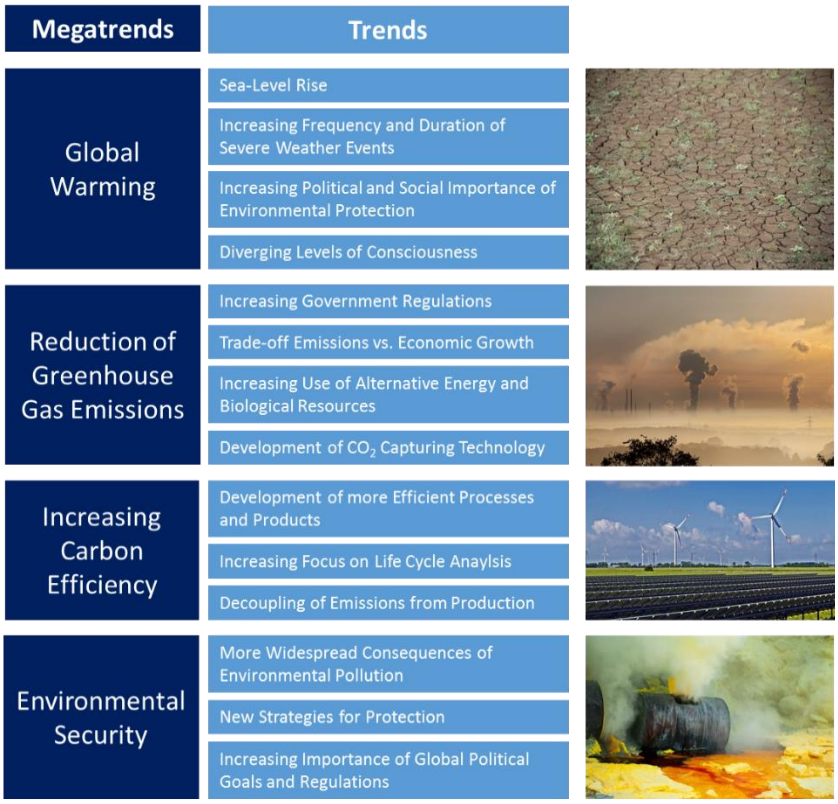

Figure 2.21: Overview of Climate & Environmental megatrends

2.1.7.1 Global Warming

Due to emissions from energy generation industrial production and transport amounting to 33 Gt in 2010, CO_2 levels in the atmosphere have increased to a record high 400 ppm leading to an increase of the global average temperature of around 1°C in the last century. Next to CO_2, which accounted for 72% of total greenhouse gases in 2010, methane (18%) and nitrous oxide (9%) emissions have also been growing rapidly in the past decades (Figure 2.22). If global emissions remain at the levels measured in 2010 the average global temperature is estimated to rise by 2.0 – 2.4 °C by 2050. If emissions continue to increase as in the past this increase is estimated to reach up to 4 °C.

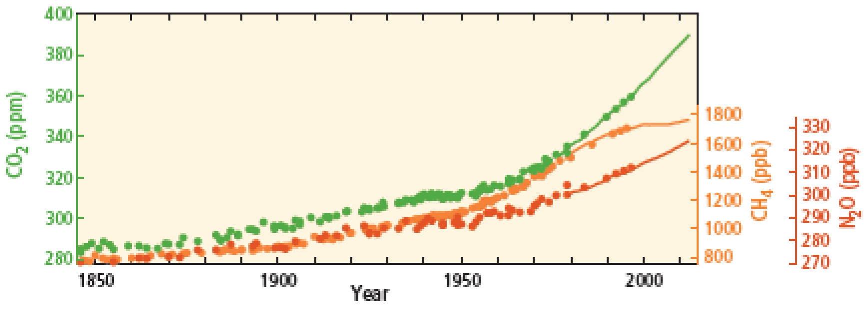

Figure 2.22: Globally averaged greenhouse gas concentrations (35)

An increasing global temperature has widespread consequences on climates, ecosystems and human health. A prevalent development is the melting of the polar ice caps leading to rising sea levels with predictions ranging from 0.3 to 2.0 m until the year 2100 (*36*). Rising sea levels present a great threat to low lying coastal regions where incidents of flooding can cause great damage and loss of life and increasing salinity of the soil may destroy valuable farmland. Another consequence of global warming is an increase in frequency and duration of extreme weather events such as heat waves, hurricanes or heavy rains which again may have disastrous consequences for humans living in the affected areas.

In light of these developments it is clear that greenhouse gas emissions need to be reduced in the next decades, although this presents an incredible challenge. Fortunately, the issue of reducing emissions and environmental protection in general has become more and more dominant on the political and social agendas with increasing governmental regulation, internationally agreed upon climate goals and a rising awareness in the general population. Nevertheless, there still exist strong differences in the level of consciousness concerning such issues around the globe. This is mostly related to the local level of economic development. (*35*).

2.1.7.2 Reduction of Greenhouse Gas Emissions

As mentioned before, in order to limit the global temperature increase to 2 °C by the end of the century CO_2 concentration in the atmosphere will need to remain near the current level not exceeding 450 ppm. Achieving this goal requires a decrease in global CO_2-equivalent emissions of 72 to 41% by 2050. Consequently, the reduction of greenhouse gas emissions is paramount if significant climate change and its dire consequences are to be avoided or in the very least mitigated. Looking at the scenarios estimated by the International Panel on Climate Change (IPCC) in Figure 2.23 it becomes apparent which effort is required to minimize the impacts of climate change, and also what the consequences of continued emission growth would be (*35*).

<table>
<tr><th rowspan="2">CO_2-eq Concentrations in 2100 (ppm CO_2-eq)
Category label (conc. range)</th><th colspan="2">Change in CO_2-eq emissions compared to 2010 (in %)</th><th colspan="4">Likelihood of staying below a specific temperature level over the 21st century (relative to 1850–1900)</th></tr>
<tr><th>2050</th><th>2100</th><th>1.5°C</th><th>2°C</th><th>3°C</th><th>4°C</th></tr>
<tr><td>450
(430 to 480)</td><td>−72 to −41</td><td>−118 to −78</td><td>More unlikely than likely</td><td>Likely</td><td rowspan="6">Likely</td><td rowspan="8">Likely</td></tr>
<tr><td rowspan="2">500
(480 to 530)</td><td>−57 to −42</td><td>−107 to −73</td><td rowspan="6">Unlikely</td><td>More likely than not</td></tr>
<tr><td>−55 to −25</td><td>−114 to −90</td><td>About as likely as not</td></tr>
<tr><td rowspan="2">550
(530 to 580)</td><td>−47 to −19</td><td>−81 to −59</td><td rowspan="3">More unlikely than likely [i]</td></tr>
<tr><td>−16 to 7</td><td>−183 to −86</td></tr>
<tr><td>(580 to 650)</td><td>−38 to 24</td><td>−134 to −50</td></tr>
<tr><td>(650 to 720)</td><td>−11 to 17</td><td>−54 to −21</td><td rowspan="2">Unlikely</td><td>More likely than not</td></tr>
<tr><td>(720 to 1000)</td><td>18 to 54</td><td>−7 to 72</td><td rowspan="2">Unlikely</td><td>More unlikely than likely</td></tr>
<tr><td>>1000</td><td>52 to 95</td><td>74 to 178</td><td>Unlikely</td><td>Unlikely</td><td>More unlikely than likely</td></tr>
</table>

Figure 2.23: Key characteristics of scenarios assessed by the IPCC (adapted from 35)

Governments are at the forefront of the endeavor to minimize global emissions. Government regulations are the main tool to achieve a reduction of industrial emissions by threatening high costs for companies that exceed defined levels either in the form of emissions taxes or fines. At the climate talks in Paris in December 2015 195 countries agreed on the first ever legally binding climate deal with the goal of limiting global warming to below 2 °C. The reductions in emissions required will only be achievable through further increased regulations and strong support for new technologies. One issue which global leaders at the Paris talks took into consideration is that with current technologies there still exists a tradeoff between emissions and economic growth. This becomes apparent when looking at the main sectors contributing to global greenhouse gas emission which are electricity and heat production (24%), Industry (21%) as well as transport and agriculture (both 14%) as depicted in Figure 2.24. Drastically limiting emissions would strongly reduce production of these sectors and therefore economic growth mainly in DEV and EM countries (*8*, *35*). This is the reason why many countries may be reluctant to impose stronger regulations in the near future and the agreement at the talks in Paris was to give less developed countries more time before demanding stronger emissions reductions (*37*).

A step towards decreasing the correlation between economic growth and emissions is the use of carbon neutral and sustainable energy and fuel sources. Power plants to generate energy from sustainable sources such as wind, hydro or solar are increasing in size, with government subsidies and new technological developments enabling sinking costs of installation and operation. Although alternative energy sources are a promising solution to decreasing emissions the energy density of such sources is low compared to fossil fuels or nuclear power. Consequently, installing the production capacities required in the future will require large amounts of space.

A similar development is the increased use of biological resources as an alternative to finitely available fossil raw materials in industrial production (*6*). Most of the technologies required for bio-based industrial production are not fully mature yet and large amounts of funding will still be invested in research towards more efficient and promising solutions.

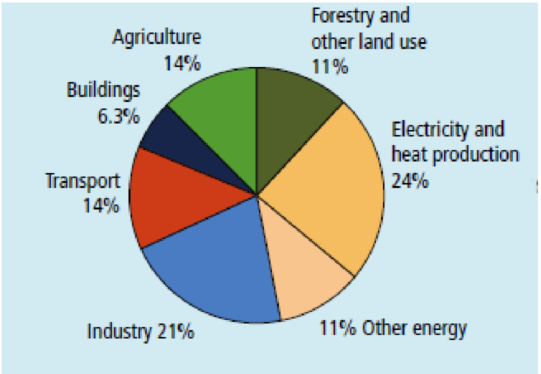

Figure 2.24: Global sources of greenhouse gas emissions by sector (35)

While these developments aim at reducing harmful emissions one can also approach the problem from a different angle and remove pollutants from the environment. Currently multiple companies and universities are working on developing technologies which remove CO_2 from the atmosphere in order to store it underground or reuse it in industrial processes. None of the techniques under development have been proven on full commercial scale yet (*38*). Although this approach could be a part of the entire solution to limiting global greenhouse gas emissions it may be more efficient and economical to focus on reducing and preventing emissions in the first place.

2.1.7.3 Increasing Carbon Efficiency

In order to limit the impact of climate change by reducing emissions while maintaining the forecast levels of global economic growth the key requirement is increasing the carbon efficiency (measured as economic output per unit of CO_2-equivalent) of electricity generation and industrial processes. This also includes the development of more efficient end products. McKinsey estimates that when accounting for global population and economic growth an increase in carbon efficiency by a factor of 10 will be required to limit atmospheric CO_2 concentration to below 500 ppm (temperature increase of around 2 °C) by 2050 (*39*). A big step towards improved carbon efficiency could already be achieved today without the development of new technologies simply by replacing outdated facilities around the globe with newer, more efficient ones. Nevertheless, in the long run new technological developments will also be required. The expected increase in stringent government regulations will serve as an incentive for companies to reevaluate their production processes and find improved solutions. The concept of Life Cycle Assessment which has become more or less standard in ADV countries will continue to increase in importance providing a holistic view along the entire value chain for the ranking of different technical solutions.

The ultimate goal of carbon efficiency improvement is to achieve a decoupling of emissions from the general production process by implementing fully carbon neutral or even negative technologies. Although we are still far away from this achievement, it will sooner or later need to be fulfilled if global economic growth is to continue in a sustainable manner.

2.1.7.4 Imperative for Higher Environmental Security

Over the past century economic growth in the ADV countries has been achieved largely without much attention to environmental considerations. As a consequence, many countries are now dealing with the long-term effects of uncontrolled waste disposal of past generations of industrial activity such as increasing proliferation of chemicals and other toxic substances. Although regulations have increased dramatically modern industrial production is still producing overwhelming amounts of hazardous waste. The disposal of these substances is far from trivial and uncontrolled release into the environment can have catastrophic and widespread consequences easily effecting many different countries. These developments have given rise to a new type of security concern which has moved to the top of national and international agendas termed environmental security. Environmental security focuses on non-traditional threats related to environmental pollution in international legal and social frameworks. As these issues are rather new and highly different from traditional security concerns, entirely new strategies will be necessary to tackle them in a responsible and peaceful manner. Furthermore, many of these problems, like for instance climate change, have multinational, if not global causes and effects. This increases the complexity of finding a solution and will require increased international cooperation in order to formulate globally binding regulations and goals (*29*).

2.1.8 Summary of Megatrends

As can be seen from the previous subchapters many areas are affected by a multitude of different megatrends. The complete overview of areas, megatrends and trends is shown in Figure 2.25.

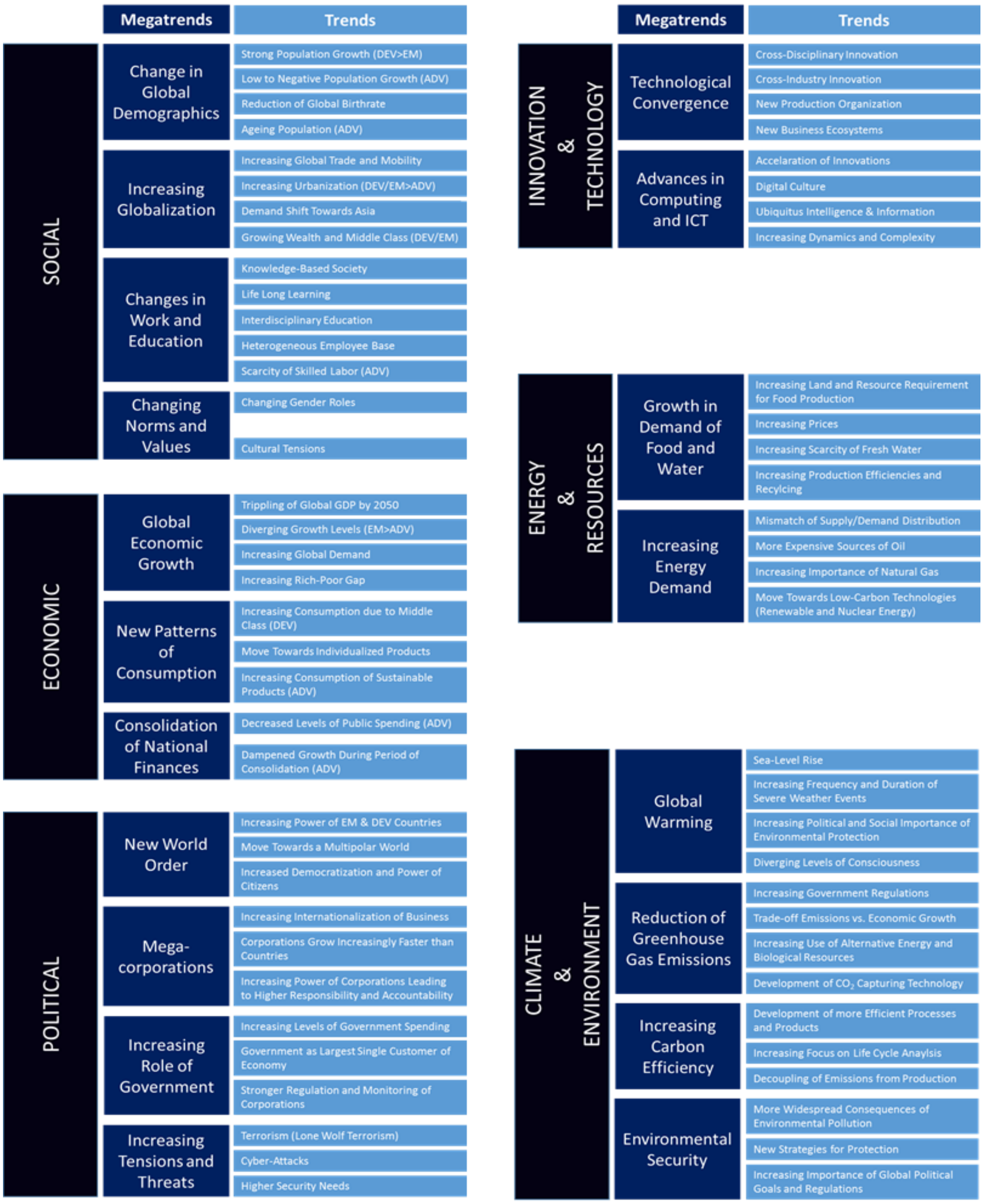

Figure 2.25: Complete overview of megatrends and trends

2.2 Connecting Global Megatrends and the Role of Marine Construction

While the previous section described individual megatrends, this section focuses on the connections between them and describes a complete chain of cause and effect focusing mainly on the global challenge of climate change (Figure 2.27). In a second step, it is argued why the focus in this thesis was set on the specific case of marine construction by demonstrating how floating infrastructure, through its application to renewable energy generation, food production, flood protection and even urban expansion, is capable of decoupling multiple linkages in the chain and thus presents itself as a promising mid- to long-term strategy for addressing these global challenges.

2.2.1 A Schematic Causal Chain for Global Future Challenges

2.2.1.1 Cause: Population Growth and Increasing Urbanization

In line with increasing wealth and knowledge advances in all areas of science, the global population has completed a period of staggering growth in the last 25 years growing from 5.3 billion in 1990 to 7.6 billion in 2018. Although the annual population growth rate is expected to decrease slightly throughout the course of the century, the medium population estimate for 2050 and 2100 are 9.8 and 11.2 billion respectively. As the demand for any good, be it food, energy, space and also services such as healthcare, scales with the number of existing consumers, the growing global population is the main driver of most large-scale future developments. In addition to this explosive population growth, global urbanization rates are also drastically increasing (from 55% in 2018 to 68% by 2050). Cities, as the largest consumers of resources and emitters of waste, will have to grow in one way or another to accommodate this huge influx of people putting additional pressure on available resources and land (*10*, *40*). Furthermore, the economies of scale offered by such concentrated urban centers enable increased productivity and the associated economic growth which further drives the overall increase in demand (*41*). Consequently, these two global developments form the starting point of the causal chain shown in Figure 2.27, leading to an increasing demand for food, mineral resources and energy.

2.2.1.2 Direct Effect: Increasing Food, Energy and Resource Demand

The production of food with enough calorific value to sustain today's global population takes up 20% of globally available landmass. Nevertheless, there are still 768 Million people worldwide that cannot get access to sufficient amounts of food (*24*). Inequality in distribution is a major cause of malnutrition. Nevertheless, redistribution of current supply is not enough to sustain the ever increasing global population. Even increases in production yield may prove insufficient (*42*). With increases in global demand for crops ranging from 70% (*25*) to 100% (*26*) from the year 2005 until 2050, an increase in global production volumes is unavoidable. With declining growth rates of global agricultural efficiency, a significant part of this increase will need to come from expansion of agricultural areas (*43*). Although the negative effects are well known even today, the clearing of natural forest represents the dominant approach to increasing available agricultural space especially in developing countries. The burning of these often huge areas of vegetation not only releases CO_2 into the atmosphere, but also simultaneously reduces the area's CO_2 storage potential (*44*). Food demand is not driven solely by population growth, but also by the globally predicted increasing levels of wealth and the associated move towards a more protein heavy, higher calorie diet (*25, 26, 45*). As the raising of livestock, specifically cattle, not only requires significantly more resources per calorie than the cultivation of crops, but is also responsible for 14.5% of global greenhouse gas (GHG) emissions and 44% of global methane emissions (*45*) food production will be a strongly increasing contributor to global GHG emissions both directly and indirectly and will take up more and more space on the global landmass if no radical changes occur.

Next to nutrition, nonrenewable mineral resources are paramount to human development and economic growth. Extraction and processing of these resources require large amounts of energy and produces large volumes of hazardous waste. Therefore, increasing demand will directly lead to increased emissions and effluents. Next to these developments extensive extraction of mineral resources has accelerated the depletion of existing high-grade deposits around the globe forcing the industry to move to deposits of lower grade minerals (*46*). Thus, larger areas need to be mined in order to obtain the required volumes of final raw material making an increasing amount of space unusable for other essential functions such as agriculture or housing. Furthermore, the extraction of lower grade ores also requires significantly more water and energy consequently producing more waste, adding to the increase in harmful emissions (*47*). Decreasing reserves of certain mineral resources may also lead to issues of scarcity in global markets, increasing the potential for conflict between exporting and importing countries (*48*).

Along with the direct need of a growing population for heat, electricity and fuel, global energy demand is further increasing due to the mentioned developments affecting food and mineral resources. Energy has always been and will continue to be a key enabler of and also a requirement for economic growth. Global energy use is estimated to increase by one third from 2015 to 2040. Despite increasing international efforts to increase the share of energy generated from renewable sources, the majority of today's energy is supplied by nonrenewable fossil fuels, dominated by oil and coal but also to a growing extent natural gas (*32*). Continued expansion in the use of fossil fuels will not only lead to massive global GHG emissions but also require extensive amounts of space for extraction, processing and conversion of these fossil resources to energy.

2.2.1.3 Indirect Effect: Global Warming, Sea Level Rise and Conflict

The most concerning effects of the emissions associated with the growth of the three previously mentioned sectors are commonly summarized under the term climate. In this paper we focus on one of the most severe effects of climate change, i.e. sea level rise, caused by the melting of the planet's ice masses and thermal expansion of the oceans as a consequence of increasing global temperatures (*35*, *49*).

Depending on the future levels of global GHG emissions, sea levels are expected to rise between 0.3 m and 2 m by 2100 (*35*). It has been estimated, that, as a consequence, in the United States alone between 4.2 and 13.1 million people will be put at risk of inundation (*36*). Globally this number will be significantly higher as all low-lying coastal regions are affected. The amount of capital and population at risk from floods has increased dramatically in recent years, and despite the construction of flood protection measures such as dikes, dams or sea walls the yearly average global flood damage more than doubled from 12.7 billion $ in 1995 to 31.7 billion $ in 2015 as shown in Figure 2.26.

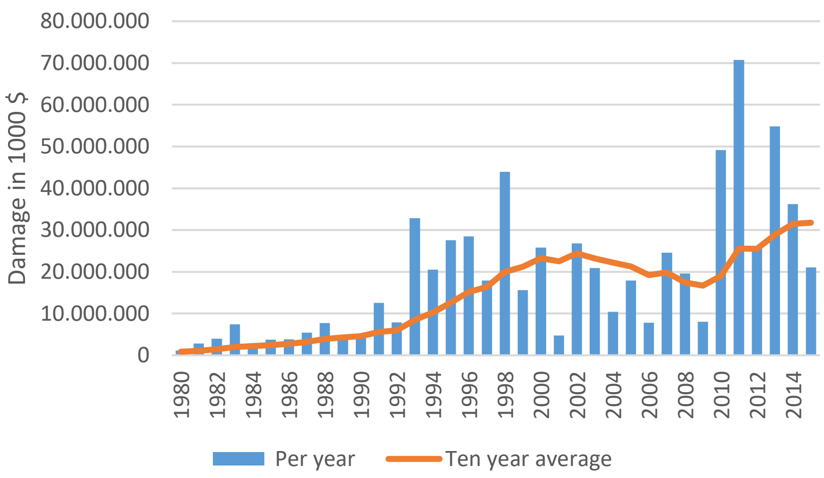

Figure 2.26: Development of yearly global flood damage (*50*)

As it is expected that half the global population will live within 100 km of the coast by 2030 and the global number of flooding events is increasing, these numbers will increase even further in the next decades (*51*, *52*). Increasingly severe incidents of flooding however do not only directly cause great damage and loss of life but may also have extensive long-term effects by increasing the salinity of the soil in the affected area, destroying valuable farmland (*53*). An extreme consequence of the combined effects of severe flooding events and a decreasing global landmass is the forced relocation of entire populations, as is already the case in certain regions in the southern Pacific (*54*, *55*). These new groups of refugees essentially fleeing from the effects of climate change will need to move to more suitable locations which tend to be existing towns or cities. The affected cities which are already expanding at a rapid rate due to other factors, will need to accommodate yet more inhabitants.

A report by de Graf estimates that the global average urban density in 2012 was 1750 inhabitants/km^2. If this density were to remain constant the addition of 5 billion people (excluding climate refuges) to the global urban population by 2100 would require an expansion of these areas by a total of 2.85 million km^2, more than half the total land area of the European Union. The report further estimates the globally available agricultural land to amount to 16 million km^2. If urban expansion were to come at the expense of agricultural land which surrounds most large cities, this would mean a reduction of global farmland by 18%. To compensate for this reduction in available land and still meet the increasing demand for food, an annual productivity growth of 2 – 2.4% would be required over the next 38 years (*56*). However, as already mentioned, the growth rate of global cereal production yield has been declining over the past decades and the majority of simulations show that they will continue to do so throughout the century especially in the face of increasing temperatures again resulting from climate change (*57*). Looking at these numbers it is clear, that at the current levels of urban density cities cannot expand far enough into agricultural land to accommodate the increasing population without severely impacting food supply security. Therefore, the only viable solution in the long term will be to increase the population density of urban areas. High population densities have been shown to be strong predictors of increased conflict potential on a local and regional level due to an increased competition for scarce resources and the fact that densely populated areas provide greater opportunities for financing and organizing of conflict (*58*). Consequently, all previously mentioned developments, which ultimately are a result of an increasing global population and rising rates of urbanization, culminate in a globally increasing potential for conflict that may reach international scales (*59*, *60*).

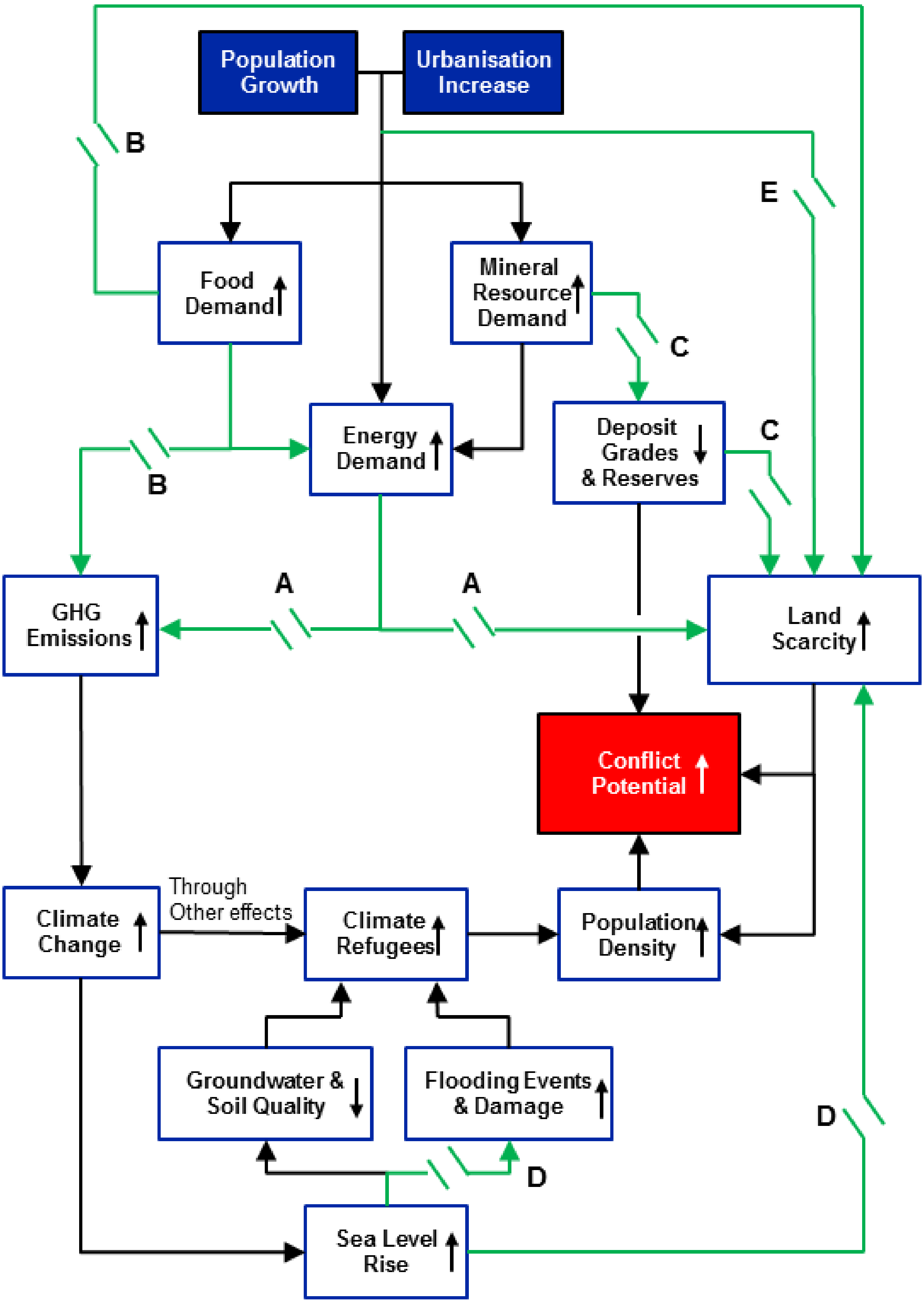

Figure 2.27: The chain of cause and effect of global warming and sea level rise with direct (D,E) and indirect (A,B,C) decoupling of cause and effect through floating construction

2.2.1.4 Addressing the Global Challenges

The complexity of the interactions leading up to and resulting from global climate change make it clear that this challenge cannot be solved with a single approach or solution. On the contrary, a combination of various technical, economic and social developments will be necessary. Consequently, the development of clean technologies and implementation of mitigation and resilience strategies is currently of central importance in many countries. Most individual strategies or technologies however focus mainly on decoupling the cause and effect between two specific developments (i.e. boxes) in the presented causal chain (Figure 2.27). Examples are renewable energy technologies aiming at decoupling emissions from energy demand, research aimed at increasing agricultural efficiency, which may decrease land and energy requirements for food production with a specific calorific output, or the development of recycling technologies which reduce the demand for virgin mineral resources. Next to these developments, which all are essential for achieving a sustainable future, floating infrastructure presents itself as an additional highly effective strategy.

2.2.2 Interrupting the Causal Chain through Floating Construction

Looking at Figure 2.27, one can demonstrate that floating construction has the potential to interrupt multiple connections in the causal chain by acting as a supporting as well as a standalone technology. As an auxiliary technology floating infrastructure can play an important role to help improve the performance of already more established research fields such as renewable energy generation, aquaculture and the extraction of alternative mineral deposits. The respective connections in the causal chain that are affected by these applications are marked in Figure 2.27 with A, B and C respectively. The concept of building on water furthermore offers a promising strategy to increasing the resilience of existing as well as future cities and communities to the direct effects of global warming induced sea level rise by rendering buildings immune to flooding (D) and by providing access to the vast unoccupied areas of the global oceans (E). The technologies that may decouple the mentioned links and the benefits of floating construction for these technologies are depicted in Table 2.1 and will be discussed in detail in the next chapters. The offshore oil and gas industry has been developing large floating structures for decades to drill for resources in deep waters. The adaption of these large-scale floating structures to other applications has been slow and only a limited number of examples exist to date, mainly due to the lack of economic viability. Nevertheless, with changing environmental values, regulations and further technological developments the huge potential this approach can have on a global scale may well be unlocked. For a review on the research related to these very large floating structures see (*61*), (*62*) or (*63*).

Table 2.1: Cause and effect of global megatrends and the impact of floating construction

<table>
<tr><th>Cause</th><th>Effect</th><th>Approach to Cut/Weaken Link</th><th>Benefit of Floating Technology</th></tr>
<tr><td>Population Growth and Increasing Urbanization</td><td>Land Scarcity</td><td colspan="2">Transition/expansion of infrastructure onto water</td></tr>
<tr><td rowspan="4">Increasing Food Demand</td><td>Land Scarcity</td><td rowspan="3">Marine aquaculture (organisms are more efficient feed-to-biomass converters than livestock and require no freshwater resources)</td><td rowspan="4">Required for move off-shore to establish, larger, more efficient farms, with lower environmental impact than near shore aquaculture</td></tr>
<tr><td>Increasing Energy Demand</td></tr>
<tr><td rowspan="2">Increasing GHG Emissions</td></tr>
<tr><td>Algae as feed for cattle to reduce methane emissions</td></tr>
<tr><td rowspan="7">Increasing Energy Demand</td><td>Land Scarcity</td><td colspan="2">Off-shore energy generation</td></tr>
<tr><td rowspan="6">Increasing GHG Emissions</td><td>Solar energy</td><td>Large areas of space available on water bodies</td></tr>
<tr><td rowspan="3">Wind energy</td><td>Majority of global power generation potential located in deep water</td></tr>
<tr><td>Improved wind conditions offshore</td></tr>
<tr><td>Lower impact on local communities (noise/view)</td></tr>
<tr><td>Ocean energy</td><td>Higher power generation potential in deeper water</td></tr>
<tr><td>Energy from biomass</td><td>Enables large scale production of algae (high material yield)</td></tr>
<tr><td rowspan="2">Increasing Demand for Mineral Resources</td><td>Declining Deposit Grades and Reserves</td><td rowspan="2">Mining of deep sea mineral deposits</td><td rowspan="2">Larger offshore processing plants improve cost efficiency</td></tr>
<tr><td>Land Scarcity</td></tr>
<tr><td rowspan="2">Climate Change and Sea Level Rise</td><td>Land Scarcity</td><td colspan="2">Transition/Expansion of Infrastructure onto water</td></tr>
<tr><td>Increasing Flood Damage</td><td colspan="2">Construction of resilient floating infrastructure</td></tr>
</table>

2.2.2.1 Decoupling Carbon Emissions from Energy Demand (A)

A step towards decreasing carbon emissions is the use of carbon neutral, sustainable energy and fuel sources. Power plants that generate energy from sustainable sources such as wind, hydro or solar are increasing in number and size, with government subsidies and new technological developments enabling sinking costs of installation and operation. The International Energy Agency estimates that energy from renewable sources will reach a share of over 25% in the USA, 30% in Japan and China and even 50% in the European Union by 2040 (*32*). The main disadvantage of renewable energy sources is that they have an extremely low energy density in comparison with non-renewable sources such as coal or natural gas (Table 2.2). Consequently, if global energy demand is to be covered entirely from renewable sources in the future an extensive amount of space will be required to install the necessary energy generation capacity (*64*). Floating technology provides the opportunity to move these large-scale plants onto the globally widely available water surfaces and provides a number of specific benefits to the individual technologies.

Table 2.2: Spatial requirement for electric power production from renewable and non-renewable sources (adapted from 65)

Source	W/m^2
Solar	**6.62**
Geothermal	**2.24**
Wind	**1.84**
Hydro	**0.14**
Biomass	**0.08**
Coal	**135.10**
Oil	**194.61**
Natural Gas	**482.10**
Nuclear	**240.81**

Moving wind power generation offshore has two advantages aside from land use considerations. The first is that wind turbines located offshore may achieve wider acceptance from the local population as the impacts concerning their visual aspects and the noise they emit are limited. More importantly however, offshore wind has a higher energy generation potential then on land due to more constant, less turbulent, and higher speed winds (*66–68*). Globally, there is an enormous potential for offshore wind with estimates of 1600 GW in Japan (*69*), 4150 GW in the USA (*70*) and 5000 GW for Europe (*71*). Most of this potential (80% for Japan and

Europe and 60% for the USA) is located in deeper waters exceeding depth of 60 m. Constructing bottom fixed foundations becomes highly uneconomical at such water depth (*72*). According to the European Wind Energy Association (EWEA) the development and installation of floating wind turbines is the only viable approach providing the necessary cost savings to gain access to these vast energy resources. The EWEA further estimates that the energy that could be captured with floating turbines in the deep waters of the North Sea alone would be sufficient to cover four times the demand of the EU thus highlighting the effect floating construction will have on the expansion of this clean energy technology (*71*).

Aside from the more established renewable energy technologies for sun and wind there is another huge alternative energy source which can be captured offshore - the power of the ocean itself. Ocean power is composed of energy present in the ocean in the form of waves, tidal movements and currents, as well as salient and thermal gradients (*73*). The theoretical power generation potential of these different sources is gigantic, estimated at 500 GW of technical potential for wave energy, 1 TW for tidal currents and up to 30 TW for Ocean Thermal Energy Conversion (OTEC) (*74–76*). Nevertheless, even the most advanced systems for harnessing these power sources are still in the early stages of development. Only a handful of prototypes of these systems are in existence worldwide and the installed capacity is minuscule compared to what may be possible in the future (Table 2.3).

Table 2.3: Comparison of global technical potential and installed capacity for ocean energy generation

	Wave Energy[A]	**Tidal Energy[B]**	**OTEC[C]**
Technical Potential [MW]	**500'000**	**1'000'000**	**30'000'000**
Installed Capacity [MW]	**6.32**	**520**	**1.32**

A:(77), B: (74), C: (78)

Once again floating construction may significantly contribute to the growth of these energy generation technologies. For instance, as average wave power is generally higher in deeper waters (*79*) floating approaches are very promising for the development of wave energy conversion systems and accounted for 67% of devices and concepts being developed in 2014 (*77*). The same is true for OTEC, the ocean energy resource with the highest technical potential. OTEC produces energy by using the temperature difference (minimum around 20 °C) between the warm surface water of the ocean and the cold water at depth ranging from 800 – 1000 m. Consequently, shore based plants are limited to areas where the topography allows access to waters of such depth directly offshore. For floating OTEC plants on the other hand suitable areas on the open ocean total about 60 million km^2 (*80*).

So far, all of these offshore energy generating technologies have only been tested as individual prototypes at different scales. The promising results show that these technologies will play an important role in the power generation of the future (*73*). The next step towards global floating renewable energy generation will be cost reduction measures through learning effects and increasing size of the individual systems. In the longer term plans are being developed to build not only single devices but entire arrays potentially combining different power generation methods to further improve the economics of such operations and harness the vast amounts of energy that are available on and in the ocean (*75, 81*).

A further highly promising source of energy gathered from the ocean is the production of third generation biofuels from algae. Additionally, certain types of algae can also be used as fish feed for aquaculture, human food or even in certain pharmaceutical applications. This high variety of applications is why the market for large scale algae farms may increase significantly in the future (*82*). In fact due to the high material yield of algal growth compared to land based plants previous studies have found that the potential amount of ethanol producible from globally grown algae is nearly four times higher than the most produced land based biofuel crop (*83*). These advantages of large-scale algae production will be explored in more detail in the following subchapter on food production.

2.2.2.2 Reducing Emissions and Land Use Intensity of Food Production (B)

Another critical issue which will need to be solved to enable a sustainable future for mankind is achieving global food security without increasing land use and GHG emissions of the agricultural sector. In the eyes of many experts the oceans will play an important role in feeding the growing world population in the future (*84–86*). Half of the globally produced biomass originates from the ocean. However, food from marine sources only accounted for 2% of global human consumption in 2006 (*87*). Aquaculture - the cultivation of aquatic plants and animals for food purposes - is growing at a rapid pace of around 7.5% per year and accounted for 44% of aquatic food production in 2014. Despite this development, the global aquaculture production volume of 74 Mt is still far behind the levels of global land based agricultural and livestock production which amounted to over 7250 Mt in 2004 (*84, 87*). The continued increase of the share of aquaculture in global food production is of paramount importance if future populations are to be supplied with sufficient amounts of food in a sustainable manner. This is due to the fact that marine organism are more efficient feed-to-biomass converters than warm blooded terrestrial animals (*88*). For instance, cattle and pigs require 7 and 4 kg of grain concentrate resp. to produce 1 kg of meat while for fish less than 2 kg are required. To produce 1 kg of grain required to feed livestock roughly 1000 l of water are used (*89*, *90*). Consequently, as fish and other marine animals are considered good sources of nutrients containing high levels of protein comparable with red meat as well as omega-3 fatty acids and high concentrations of vitamins and minerals (*91*), aquaculture presents a far more efficient solution to meeting growing protein demands than further expanding land-based livestock production. The greatest benefit is provided by aquaculture conducted in the ocean with species accustomed to salt water as this does not put additional pressure on already shrinking freshwater resources and doesn't further occupy valuable space on land (*92*). However, in coastal regions space for aquaculture farms is already getting scarce since it competes with public use of this space. Furthermore, extensive near shore aquaculture has detrimental effects on the local environment such as eutrophication, pollution from waste or transmission of disease to wild species (*87*, *93*, *94*). The construction of floating farms offshore provides the opportunity to increase aquaculture production while minimizing these negative effects. The stronger currents and larger water masses in offshore locations allow for a greater natural dilution and dispersion of waste and the installation of larger, especially deeper cages which has been shown to lead to an increase in growth rate and decrease in mortality of the cultivated species (*94–97*). Consequently, the largest future environmentally sustainable expansion of aquaculture is believed to take place further offshore in the oceans potentially reaching as far as the high seas (*98*). Unsurprisingly, interest in the development of floating solutions for aquaculture has increased significantly (*94*, *99–102*). An example of the endeavor to move aquaculture offshore is the establishment of Ocean Farming, a subsidiary of the Norwegian SalMar group. Ocean Farming is currently building a full-scale prototype of a semisubmersible offshore fish farm for the cultivation of salmon (*103*). As salmon farming has become a very important industry for the Norwegian economy with a total production of 1.2 Mt in 2014, the government is attempting to realize the high growth scenario of increasing the countries salmon production to around 5 Mt by 2050 (*104*). According to Ocean Farming this ambitious goal will require 7-8 floating farms to be built every year. These numbers are only for one marine species in one country and thus highlight the global potential for floating construction in the growing sector of offshore aquaculture.

Algae are another specific product from aquaculture which may provide a multitude of solutions to the issues at hand. As algae has significantly higher material yields than any land-based crop algal farms offer one of the most efficient uses of space of any crop (*83*). The versatile use of different algae species is however where the true potential lies. As already mentioned, algae can be processed to produce third generation biofuel, used as feed for fish and livestock, is suitable for human consumption and also certain pharmaceutical applications (*105–108*). Furthermore, these plants can be grown in brackish or salt water and hence neither compete for land nor freshwater resources. Algae also absorb nitrogen, phosphorus and carbon found in wastewater streams as nutrients for their growth and consequently can provide wastewater treatment as well (*109, 110*). A recent discovery has added to this list of beneficial properties of algae. Kinley et al. reported that addition of 2 - 5% of *Asparagopsis taxiformis, a species of red macro algae,* to livestock feed reduces methane production by over 99% in vitro (*111*). First in vivo tests conducted with sheep showed that addition of 2% algae to the animals feed reduced methane emissions by 50 – 70% over a period of 72 days (*112*). However, it was calculated that to supply enough algae for 10% of Australia's cattle industry 6000 hectares would be necessary (*113*). Therefore, once again floating construction may provide the best opportunity to expand algal farms onto areas large enough to produce the amounts necessary to provide the described benefits on a global scale (*100*).

It must however also be mentioned that there exist a number of further limitations for large scale expansion of global aquaculture which cannot be solved by moving to the open oceans. For instance, the main obstacle to increasing salmon production in Norway are parasites known as sea lice which reduce growth and increase mortality rates of farmed fish stocks (*114*). Another major challenge for aquaculture growth is the sustainable production of sufficient quantities of feed. Many farmed species – especially carnivorous fish – rely on feed derived from wild fish stocks specifically fish meal and fish oil (*86, 88*). An option to decrease this dependency on wild fish stocks is to substitute these products in the feed mix by animal or plant protein. However, this leads to aquaculture tying into the agricultural supply chain thus contributing to the issues of increasing land-based food production and cancelling out the potential advantages thought after in the first place (*115*). Consequently, one of the most important goals for aquaculture is to decouple feed production from wild catches and land-based agriculture. Possible solutions being discussed are the extraction of single cell oils from microorganisms such as algae, or the use of by products from terrestrial animals (meat, bone meal, blood meal) or seafood processing (*116*). Despite these remaining challenges, the described examples illustrate how floating infrastructure could enable a widespread growth of offshore aquaculture thus indirectly providing a significant contribution to reducing carbon emissions, as well as resource and space requirements of global food production, while potentially even meeting the rising demand in protein heavy nutrition.

2.2.2.3 Decreasing Scarcity of Mineral Resources (C)

For many countries without large resource deposits supply security is a more immediate and pressing issue than the amount of worldwide ore reserves available. Global distribution of land-based mineral reserves is mostly highly concentrated leading to a handful of countries with large control over global markets for certain raw materials (*48*). Due to the criticality of minerals for modern societies and economic development, importing countries are looking for alternative sources to cover their raw material demand. In the course of these investigations deep sea mining (DSM) has reemerged as a possible solution in the medium to long term (*117*, *118*). In short the process of DSM involves excavation and collection of minerals on the sea floor at depth ranging from 1000-6000 m, transportation of the ore through a riser system to a surface support vessel (SSV) where it is subsequently dewatered and transported to land for further processing in order to extract valuable raw materials. These mineral deposits can be classified into three distinct types, seafloor massive sulfides, polymetallic or manganese nodules and cobalt-rich ferro-manganese crusts. According to a report by ECORYS (*119*), which was conducted in scope of the Blue Mining project of the European Union, DSM could contribute to the expansion of the resource base and increase supply security for a number of essential minerals as shown in Table 2.4.

A central component for advancing the development of the DSM process is the SSV. Larger vessels or platforms could improve the economics of the process in two ways. Firstly, an increased storage capacity would mean less frequent transport of the ore from the site to land will be required, decreasing the costs for additional supply vessels. Furthermore, the transport of dewatered, unprocessed ores is rather inefficient as a large amount of unwanted sediment and minerals is transported with the valuable ore. Larger SSVs could provide room for more equipment allowing more extensive (pre)processing of the ores on site significantly improving the economics of the entire operation (*120*).

Considering the current market prices for most metals and the technological development level of mining equipment, DSM is not yet a commercially viable venture. Most of the activity is focused on exploring potential deposits and assessing their mineral compositions. Worldwide only two licenses have been granted for actual mining of the seabed and only one company is actually close to beginning extraction (*121*). A further major concern surrounding the concept of DSM are the associated environmental impacts, which are still largely unknown (*122*, *123*). A first long-term study conducted by GEOMAR shows that even 37 years after a major disturbance, ecosystems located at depth of around 4000 m show little to no signs of regeneration (*124*). This leads to the assumption that DSM will have severe long-term impacts on deep sea ecosystems. Consequently, this topic is the most controversial in our discussion of the potential of floating construction. It may decrease global conflict potential by decreasing scarcity for a number of major mineral resources. However, increased development of recycling technologies and infrastructure most likely presents a more sustainable approach for expanding the existing resource base of non-producing countries.

Table 2.4: Potential impact of deep-sea mining on global metal markets (based on data from *119*)

Elements	**Impact of Deep-Sea Mining on**	
	Global Supply	**Supply Security for Importing Nations**
Copper	**Low**	**Low**
Nickel	**Low**	**Low**
Zinc	**High**	**Medium**
Cobalt	**High**	**High**
Manganese	**Medium**	**Medium**
Gold	**Low**	**Low**
Silver	**Low**	**Low**
Platinum Group Metals	**Medium**	**High**
Rare Earth Elements	**High**	**High**

2.2.2.4 Increasing Resilience to Flooding Events (D)

As with other severe weather events, the number of flooding related incidents has increased substantially in the past decades as a result of climate change (Figure 2.28). Consequently, the resilience of infrastructure to such disasters is an increasingly important consideration for coastal communities. As mentioned, traditional flood protection measures have proven insufficient in many cases over the past decades. Floating construction offers an alternative approach, shifting the goal from fighting against to living with water both for land-based and permanently floating structures. On land buildings can be constructed on buoyant foundations which are connected to mooring pylons. In the case of a flood the entire building can rise with the increasing water level thus dramatically decreasing potential damage. Permanently floating structures (i.e. structures that are always located on a body of water) show the same behavior in case of rising water levels and additionally are unaffected by earthquakes, since they are isolated from the ground. This increased resilience can be highly beneficial for crucial infrastructure functions such as power generation. In addition to the ability to withstand earthquakes, floating power plants located in deeper waters (ca. 100 m) can also survive a subsequent tsunami without damage (*125*). Thus, in the event of such natural disasters floating power plants could limit damage and casualties by keeping power running after the event, enabling better emergency responses (*126*).

In the long-term future the construction of truly large-scale floating islands able to carry entire communities may furthermore eliminate the need for populations affected by sea level rise to relocate to other countries altogether (*127*, *128*). For example, the Pacific Island nation of Kiribati, which may likely fall victim to see level rise in the next decades is evaluating the construction of such islands as an adaption measure (*129*). However, the estimated costs of construction greatly exceed the small nation's financial capabilities (*130*), underlining the importance of further research into the development of such large-scale structures.

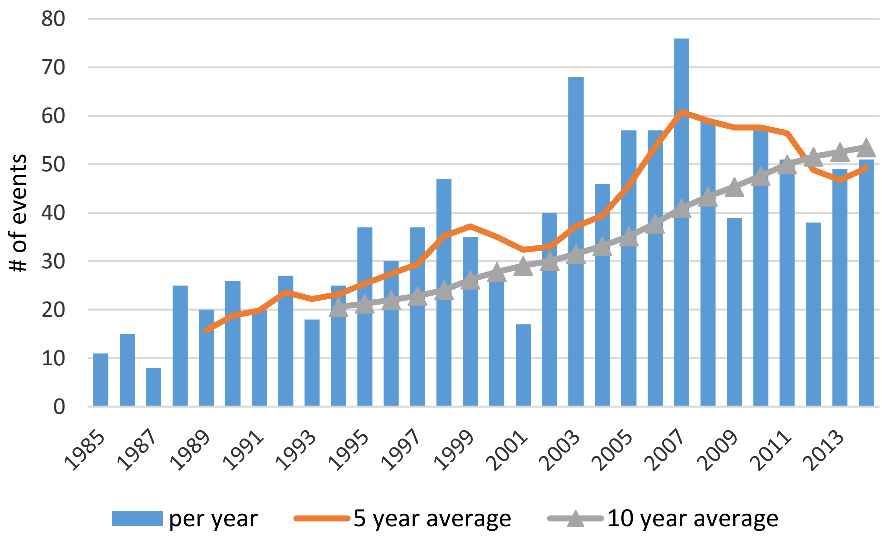

Figure 2.28: Historical development of extreme flooding events (52)

2.2.2.5 Urban Expansion without Land Use (E)

The surfaces of lakes, rivers or oceans are largely unoccupied and space on water is abundantly available in most major cities compared to space on land. Around 70% of the earth's surface is covered by oceans, a total area of slightly more than 360 million km^2, which is up to date (with a few exceptions) used solely for transportation of people and goods (*131*). Floating construction would open up these spaces for urban expansion consequently mitigating land use conflicts and reducing the necessity for increasing urban population density. Buildings placed on large floating platforms additionally provide urban planners with much needed flexibility in the light of ever increasing magnitude and speed of changes required to provide a satisfactory urban environment. Such changes are usually very difficult to anticipate causing buildings to be demolished as soon as they are no longer required, or the specific space can be used more economically by a building of another function. This is often done long before the structural stability of these buildings actually becomes critical. As floating structures are only kept in place by a certain type of mooring it is possible to move them from one position to another, thus eliminating the need for demolition in the wake of urban development. This substantially increases the lifetime of such structures leading to a more efficient use of construction materials and other resources (*127*). Considering that waste from construction and demolition is one of the largest waste streams on the planet with 970 million tons produced in Europe alone in 2006 (*132*) and recycling rates for these waste materials ranging from 47% in Europe to a mere 5% in China (*133, 134*) adaption of this new expansion strategy may greatly improve the sustainability of urban development in the future. For this, a modular form of construction may prove advantageous, as it can limit the costs and also increase the stability of the resulting platforms.

2.3 Driving the Development of Floating Infrastructure

As shown in the previous subchapter, floating construction has the ability to improve the performance of renewable energy generation, increase more efficient food production by enabling widespread growth of offshore aquaculture and (if feasible from an environmental perspective) provide access to extensive mineral reserves located on the bottom of the ocean, if implemented on a larger scale. Furthermore, it will also play an important role in increasing the resilience of coastal communities by minimizing damage to central infrastructure functions caused by increasingly frequent and severe flooding events. Finally, in the longer term floating construction has the potential to mitigate land use conflict as it opens up the vast areas of the planet which are covered by water for sustainable urban expansion.

2.3.1 Current Development Status of Floating Infrastructure Applications

In principle any infrastructure function can be adapted from the land-based state to a floating approach. The complexity of this adaption varies depending on the type of infrastructure. Also, there are certain applications for which it makes more sense to move them onto the water than for others and even a few, for which a floating approach would be highly beneficial. Figure 2.29 provides an overview of potential types of floating infrastructure, some are already mature, and others still in the developing stage while some are just concepts that could become reality in the longer term. Various existing and planned projects for the applications shown in Figure 2.29 will be briefly described in the following subsections.

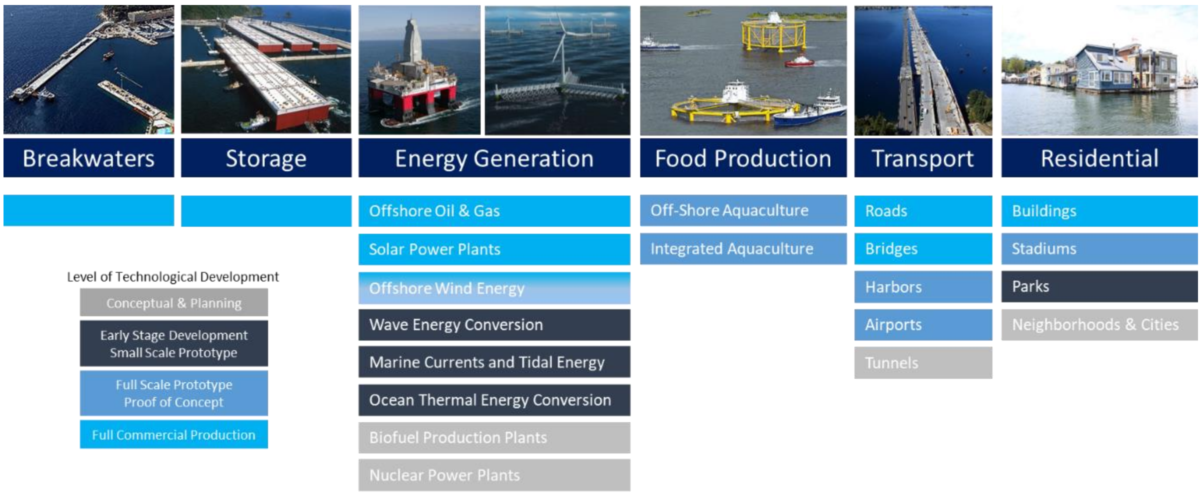

Figure 2.29: Overview of potential applications for floating infrastructure and their current state of development

2.3.1.1 Breakwaters

Floating breakwaters have been constructed on a larger scale since the 1970s, a time where the demand for harbors exceeded the amount of suitable locations in shallower water (*135*). While the first floating breakwaters were rather small, they have since grown into concrete structures of gigantic proportions. Currently the world's largest floating breakwater is located in Monaco. It is 352 m long, weighs 167'000 tons and with an estimated construction cost of $250 mil. The structure is so large that it contains a shopping mall and a parking garage in its hollow interior and functions as a dock for up to four cruise ships at a time (Figure 2.30). Thus, it is a prime example of the potential for floating structures fulfilling multiple functions at a time.

Figure 2.30: Floating breakwater in Monaco: View of harbor and breakwater (Left), Breakwater during construction (center), Idealized image of cross-section (right) (136)

Global developments point to the fact that the demand for floating breakwaters will increase in the future. For instance, the size of large seagoing vessels is continuously increasing requiring existing harbors to expand and new harbors to be placed in ever deeper waters, thus necessitating the use of floating breakwaters. If human beings are to move further and further out onto the water in the future breakwaters will become an ever more essential piece of infrastructure for the protection of property and human life.

2.3.2 Storage Space

To date, large floating storage facilities exist only in Japan, a nation that is already dealing with the issue of land scarcity. The Japanese facilities were built to store oil and different kinds of fuel in case of a possible oil crisis. The larger facility built in Shirashima is made up of eight floating steel structures (397 x 82 x 25.4 m each) and can in total hold up to 5.6 mil. m^3 of fuel. This is enough to cover the entire country's oil consumption for a day. The second facility located in Kamigoto consists of five units (390 x 97 x 27.6 m each) with a total capacity of 4.4 mil. m^3 (*63*). Both facilities are shown in Figure 2.31.

Figure 2.31: Floating oil storage facilities in Japan: Shirashima (Left), Kamigoto (Right) (137)

Although to date only these two large facilities have been built it would be possible to also relocate container terminals, warehouses or other physical storage facilities from land to water, thus freeing up valuable space for other infrastructure. In fact, the idea of a floating container terminal was already discussed to allow for quicker transfer of containers between two vessels (*138*). In general, the increasing size of transport vessels around the globe would profit from floating terminals in deep water to unload their cargo, thus freeing up the waterways and ports further inland for smaller more maneuverable ships.

2.3.3 Energy Production

2.3.3.1 Oil and Gas

Floating structures are today already providing huge economic benefits to those companies that were willing to take the risk and invest in the concept. In fact, the development of floating structures for the exploitation of deep-water oil and gas reserves goes back to the middle of the 20th century. Starting in the late 1940s offshore structures were used to extract crude oil from beneath the oceans floor and processes it on site before transport to shore. While the first off-shore structures were still bottom founded the move to ever deeper waters led to the develop-ment of floating oil platforms by the 1960s. Figure 2.32 provides an overview of the different types of oil platforms used today.

The most common structure for floating oil platforms is the semisubmersible design used for tension leg platforms and floating production systems. This type of platform consists of a set of pillars, beneath the actual platform that are partially filled with water in order to submerge the lower part of the structure thus providing high stability through the low center of gravity. Newer semisubmersible rigs often have engines to move on their own but can also be loaded onto gigantic cargo vessels if they need to be transported over larger distances. Once at the desired location the rigs are held in place by mooring them to the seafloor or by using their engines and a dynamic positioning system. Currently, over 220 semisubmersible rigs are in operation around the globe, the largest of which weigh up to 30’000 tons and cost around $750 mil. to build (*63*).

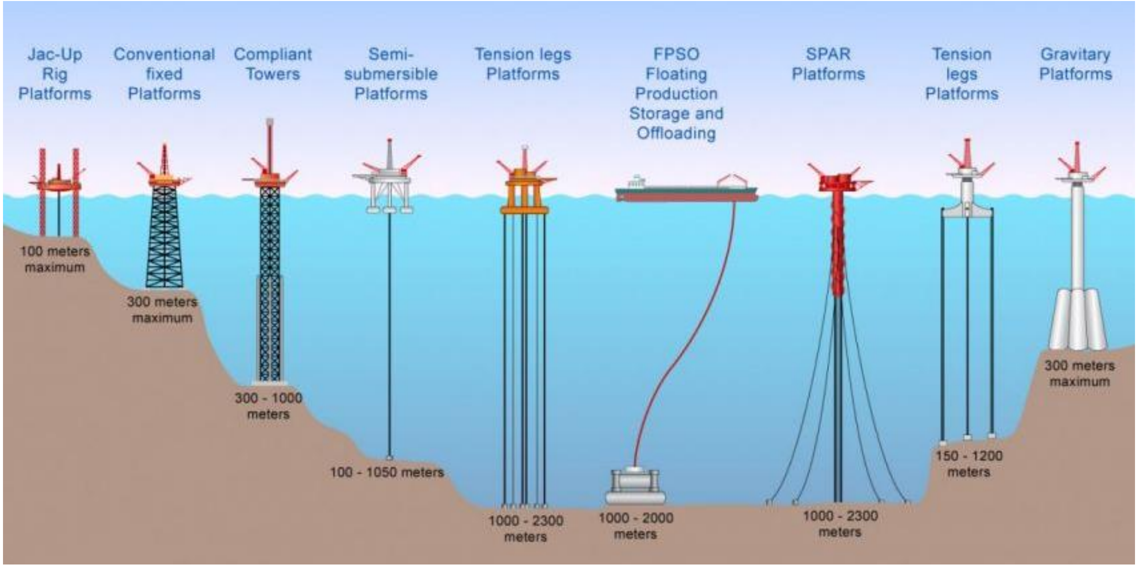

Figure 2.32: Types of offshore oil rigs and platforms (adapted from 139)

Another type of floating structure used for drilling in ultra-deep water is the spar. A spar structure is basically a long vertical cylinder with a deck on top. The two main types of spars are the classic and the truss spar. The deep draft of the spar limits the topside motion significantly compared to the semisubmersible structure. Originally spars were used mainly as marker buoys or for gathering of oceanographic data. The first spar for use in the oil and gas industry was constructed by Shell in the 1970s and served as an oil storage. The world’s largest spar (in terms of water displacement) was constructed in South Korea and deployed in the Aasta Hansteen oilfield on the Norwegian continental shelf in 2018. The entire structure is 193 m long, with a diameter of 50 m and cost an estimated $5.4 bil. to develop (*140*). Due to the higher price for the construction of spar platforms they are far less common then semisubmersibles and used only when the increased stability in ultra-deep water is required.

Although floating platforms developed for the industrial production of oil and gas are far from the hospitable environment required of a residential neighborhood in a city, they are an impressive demonstration of the technical feasibility of large, stable floating structures in the open oceans. For the future production of floating infrastructure for other applications the know-how and experience that the ship building and oil companies have gathered through off shore drilling will be an invaluable asset.

2.3.3.2 Renewable Energy

2.3.3.2.1 Solar Energy

A number of larger floating solar power plants already exist around the globe (Figure 2.33). In 2018, the world's largest floating solar power station was located near the city of Kobe, Japan. The plant will consist of 51,000 solar modules, covers an area of 180,000 square meters, and generates enough electricity to power approximately 4,970 typical households (*141*). For the Japanese, who already today are dealing with land scarcity, floating solar power production is a highly interesting opportunity underlined by the fact that the company involved in the construction of the Kobe plant is working on developing at least ten more large scale facilities. Other countries such as the U.S., the U.K., France, Australia, India, China and Brazil have also started initiatives to develop large scale floating solar power plants, leading to a growth rate for floating solar power that is expected to amount to a CAGR of 65.1% from 2016–2023 reaching a valuation of $842 mil. in 2023 (*142*).

Figure 2.33: Floating 70 MW solar power plant in Kagoshima, Japan (63)

2.3.3.2.2 Offshore Wind Energy

In 2016, a handful of European countries were by far the global leaders in offshore wind capacity, responsible for 91% of all global installations amounting to 11'034 MW of power generation capacity. The only other countries with installed offshore generation capacity at the time were China, followed by Japan and South Korea (Figure 2.34). The USA was beginning construction on its first commercial project and India had just started to develop an offshore wind roadmap for the future (*143*). The upside potential for the offshore wind energy market is gigantic, many countries still being far from their goals of installed capacity set for 2030 or 2050.

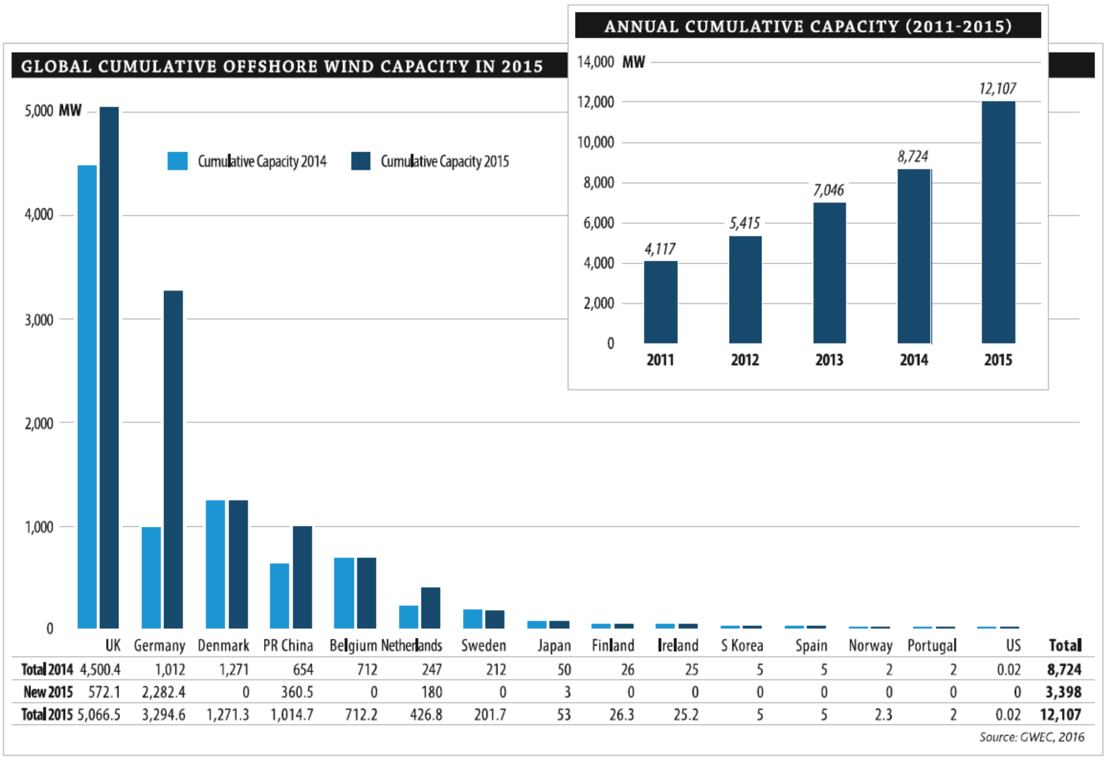

Figure 2.34: Global overview of cumulative installed wind capacity (143)

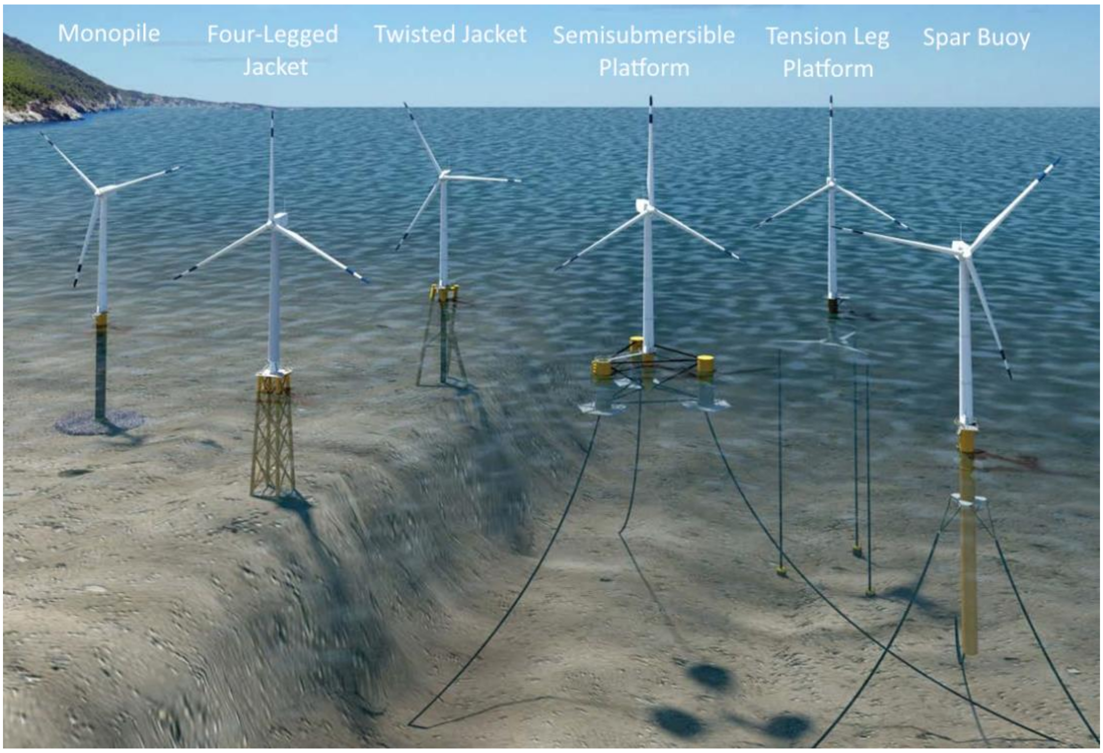

Figure 2.35: Substructure types for offshore wind turbines (adapted from 144)

As in oil and gas, the first step towards offshore wind power generation was to construct bottom fixed turbines as is the case for almost all the currently installed systems globally. However, the current trend in the industry is the move towards deeper waters and larger turbines (*68*). For some countries, such as Japan or the US, extensive wind energy resources are located predominantly deeper waters, making the construction of bottom fixed turbines uneconomical to begin with and necessitating a floating approach. The different substructure designs for offshore wind turbines are similar to those already developed in the oil and gas sector, as can be seen in Figure 2.35. The floating turbine technology is less developed and to date only a few prototypes have been installed. This is due to the increased complexity surrounding the design and construction of durable floating substructure as well as the increased costs of production and maintenance (Table 2.5). Nevertheless, these projects have served to demonstrate the feasibility of floating substructures and have drastically increased investor confidence in their reliability and performance. As a consequence, other countries with deep water offshore wind resources, such as China, the UK, Norway, Spain, Italy, Portugal and Korea, are showing great interest in floating wind turbines. This is exemplified by the list of projects that are currently active around the globe shown in Table 2.6. The major barrier to offshore wind energy is the high cost of these facilities compared to land-based ones. Nevertheless, it is expected that through increasing installed capacity, larger turbines, greater competition and further development of the supply chain these costs can be reduced to compete with those for onshore wind power by 2025-2030 (*145*).

Table 2.5: Investment costs for offshore wind power at varying water depth (€/kW) (146)

	Water Depth (m)			
	10 - 20	20 - 30	30 - 40	40 - 50
Turbine	772	772	772	772
Foundation	352	466	625	900
Installation	465	465	605	605
Grid Connection	133	133	133	133
Others	79	85	92	105
Total Cost	1800	1920	2227	2514

Table 2.6: Global proposed full scale floating wind energy projects through 2020 (144)

Project	Lead Organization	Status	Country	Turbine Capacity (MW)	Project Capacity (MW)	Water Depth (m)	Foundation Type	Year Online	Description
Hywind Demo	Statoil	Installed	NO	2.3	2.3	220	Spar	2009	First full-scale floating turbine (Siemens) on a Hywind spar foundation
WindFloat Atlantic I	Principle Power, Inc.	Installed	PT	2	2	50	Semisubmersible	2011	Second full-scale turbine (Vestas) on a three-column WindFloat semisubmersible foundation (Principle Power)
Kabashima/ Goto	MOE	Installed	JP	2	2	91	Spar	2013	Two-MW Hitachi turbine on a hybrid concrete-steel spar foundation
Fukushima Forward I	METI	Installed	JP	2	2	120	Semisubmersible	2013	Two-MW turbine (Hitachi) on a four-column semisubmersible foundation (Mitsui), as well as a 66-kV floating substation on an advanced spar foundation (Japan Marine United)
Fukushima Forward II	METI	Under Construction	JP	7.0; 5.0	12	120	Semisubmersible; Spar	2015/ 2016	Seven-MW turbine (MHI-Vestas) on a V-shaped semisubmersible foundation (MHI) and a 5-MW turbine (Hitachi) on an advanced spar foundation that incorporates heave plates (Japan Marine United)
FLOATGEN	Ideol; Adwen	Approved	FR	2	2	45	Semisubmersible	2016	Two-MW turbine (Gamesa) on a concrete semisubmersible foundation featuring damping pool technology (Ideol)
GICON SOF Pilot	GICON	Approved	DE	2.3	2.3	20	Tension-Leg Platform	2016	A 2.3-MW turbine (Siemens) on a tension-leg platform (GICON); likely to be the first operating wind turbine on this type of platform in the world
Hywind Scotland	Statoil	Permitting	UK	6	30	100	Spar	2017	Five 6-MW Siemens turbines on Hywind spars (Statoil) in Scotland
WindFloat Atlantic II	Principle Power	Permitting	PT	6.0–8.0	25	100	Semisubmersible	2017	Three- to four-turbine array on a WindFloat semisubmersible (Principle Power)
VERTIWIND	Technip; Nenuphar	Approved	FR	2	2	50	Semisubmersible	2017	Two-MW vertical-axis turbine on a semisubmersible foundation
SEA REED	DCNS; Alstom	Planning	FR	6	12	70	Semisubmersible	2018	Two 6-MW Alstom turbines on steel substructures (WindFlo)
WindFloat Pacific	Principle Power	Permitting	US	6.0–8.0	30	350	Semisubmersible	2018	Up-to-25-MW project on WindFloat semisubmersibles (Principle Power) off Coos Bay, Oregon
Kincardine	Pilot Offshore Renewables	Permitting	UK	6.0–8.0	50	100	Semisubmersible	2017	Proposed 50- MW project using WindFloat semisubmersibles (Principle Power)
Aqua Ventus I	DeepCWind	Permitting	US	6	12	100	Semisubmersible	2018	Two 6-MW turbines on a concrete semisubmersible foundation and composite tower; a 1/8th-scale prototype was demonstrated in the Gulf of Maine in 2013
Dounreay	Highland and Islands Enterprise	Planning	UK	6.0–8.0	30	85	Floating	2018	DBD Systems Eco-tension-leg platform proposed for one or more sites; combines a concrete tension-leg platform with a concrete gravity anchor
Oahu NW Lease Request	AW Hawaii Wind, LLC	Planning	US	6.0–8.0	408	850	Semisubmersible	2019	Developer submitted an unsolicited lease application for a commercial array with WindFloat semisubmersibles in Hawaii
Oahu South Lease Request	AW Hawaii Wind, LLC	Planning	US	6.0–8.0	408	600	Semisubmersible	2019	Developer submitted an unsolicited lease application for a commercial array with WindFloat semisubmersibles in Hawaii
Fukushima Forward III	METI	Planning	JP	TBA	100	-	TBA	2020	Large commercial installation that expands upon the Fukushima Demonstration Projects (Phase I and II)

2.3.3.2.3 Wave Energy

Wave energy generation is a very interesting development for floating construction with 67% of current concepts being of the floating type (*77*). There are three different broad technology types in existence for the construction of a wave energy conversion system: oscillating water columns, oscillating bodies and overtopping. Oscillating water column systems have a semi submerged chamber, with an air pocket above a column of water. Wave action forces this air out and back into the chamber. The air is channeled through a turbine generator and produces energy. Since the turbine is the only movable part in these systems, they are very reliable. Prototypes of these systems have been built in the UK, Spain, Portugal and Australia (*75*). The OE Buoy system located of the coast of Ireland is an example for a floating prototypes and is capable of producing 2.8 MW of power (Figure 2.36) (*147*).

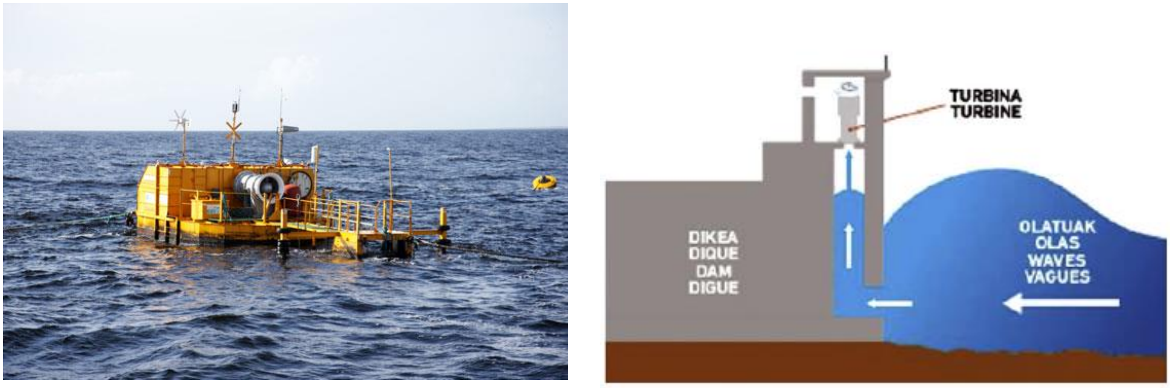

Figure 2.36: OE Buoy (left), schematic of a coastal system (right) (148)

Oscillating bodies are more complex systems usually designed for deeper waters. They generally have a floating body which oscillates due to the waves. There are many different options to transform the kinetic energy of this oscillation into electricity which is the reason for the various designs for these systems. To date no clearly favorable technology has emerged yet and most prototypes are just undergoing the first full scale tests or still under construction. Examples for prototypes of floating oscillating body systems are the PowerBuoy and AWS in the US or the Pelamis II in the UK (Figure 2.37).

Figure 2.37: Examples of oscillating body wave energy converters: Pelamis II (left), PowerBuoy (right) (75)

The final wave energy conversion systems are the overtopping devices. They work by focusing waves towards a central point where the water overtops a ramp and is retained in a reservoir. After enough water has been collected in the reservoir it is released back into the sea through turbines transforming the potential energy into electricity. These systems are very simple but need to be rather large to produce sufficient amounts of energy. To date, the only large-scale prototype of a floating overtopping system is the WaveDragon which was successfully tested in Denmark. In a sense it is a floating hydroelectric dam 58 m in length, weighs 273 tons and has a power rating of 20 kW (Figure 2.38). The full-scale systems is planned to weigh up to 33’000 tons, have a total length of 300 m and be capable of producing 7 MW of power (*149*).

Figure 2.38: 20kW prototype of the WaveDragon system (150)

2.3.3.2.4 Tidal Energy

Unlike wave energy converters, tidal energy conversion systems harness the energy present in the currents and tides beneath the waves. The two main technologies are tidal range and tidal current. Here the focus is put on tidal current or tidal stream energy generation, since tidal range systems are bottom fixed dams and therefore not relevant for floating technology. Tidal current systems on the other hand can be either bottom fixed (gravity structures or piled structures) or floating (Figure 2.39). No clearly superior concept has emerged to date with 36% of all tidal stream concepts involving floating substructures, 60% bottom fixed and 4% unspecified (*151*).

In general, the energy is produced by turbines similar to wind turbines. The material requirements for these tidal turbines are a lot higher than for those on land, since they are constantly submerged. Furthermore, due to the increased density of water, the forces enacted on the rotor blades are significantly higher than in air. This is also an advantage for tidal power generation, as the high density of water allows it to function at very low water velocities of 1.5–2 m/s (compared to 4-5 m/s for wind). The development of these technologies has taken huge steps in the past decade with over 40 systems being introduced. Nevertheless, most of these are just concepts and only a handful of systems have been tested at full scale. Table 2.7 provides an overview of the largest prototype turbines installed and connected to an electrical grid to date.

Table 2.7: Overview of fully developed tidal power prototype projects

Project	Lead Organization	Country	Turbine Capacity (kW)	Foundation Type	Year Online	Image
HS1000	ANDRITZ HYDRO Hammerfest	UK	1000	Seabed Mounted Pile	2011	
Oceade	Alstom TGL	UK	1000	Seabed Mounted Pile	2013	
Open-Center Turbine	DCNS Open Hydro	UK/FR	500	Gravity Base	2008/2016	
SR250	Scotrenewables Tidal Power	UK	250	Floating	2012	
SeaGen S	Atlantis Resources/MCT	UK	1200	Seabed Mounted Pile	2008	
HyTide 1000	Voith Hydro	KOR	1000	Seabed Mounted Pile	2013	
AR 1000	Atlantis Resources	UK	1000	Gravity Base	2011	

Information taken from main project websites

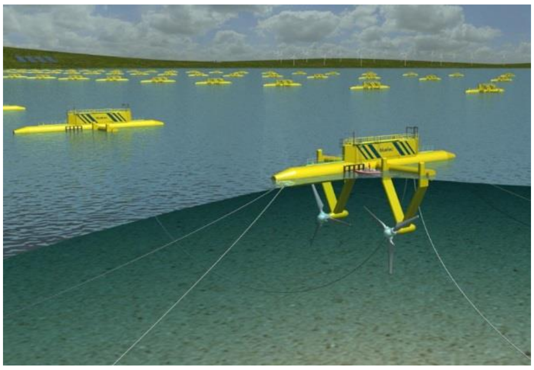

Figure 2.39: Tidal power generation: fixed bottom system (152) (left), floating system (153) (right)

2.3.3.2.5 Ocean Thermal Energy Conversion

OTEC produces energy by using the temperature difference between the warm surface water of the ocean and the cold water at depth ranging from 800–1000 m. In a flash evaporator or heat exchanger warm water is used to produce vapor that is used as a working fluid to drive a turbine that produces electricity. The cold seawater cools the vapor at the outlet of the turbine condensing it back into a liquid. The vapor pressure difference in the turbine is caused by the temperature difference between the warm and cold seawater. Auxiliary power is required to pump the seawater from the deep. This power is directly supplied by the output of the entire OTEC system. Figure 2.40 shows the basic principle of the OTEC process.

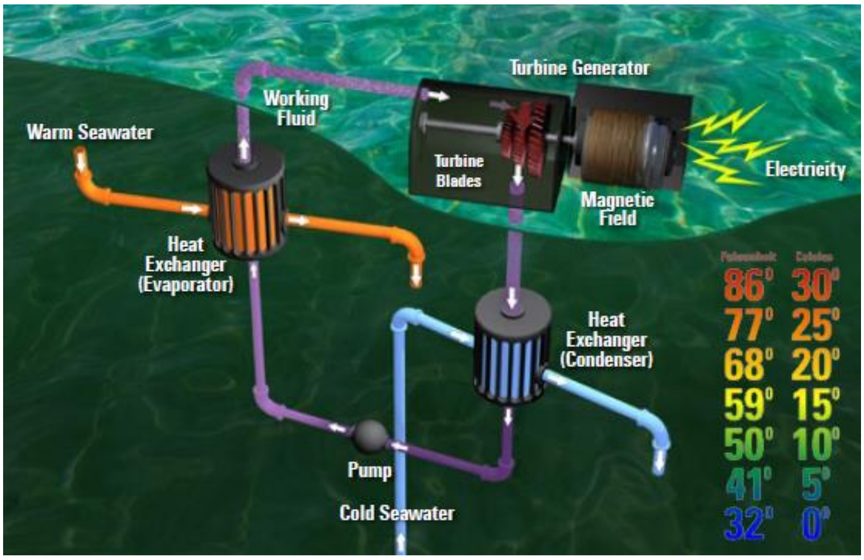

Figure 2.40: Basic principle of the OTEC process (154)

So far only a handful of OTEC plants with up to 1 MW of capacity have been constructed. While some are located on shore, floating installations are very promising for OTEC plants since they can be placed in areas with the required minimal water depth. These small-scale applications have shown that the technology in itself works. The main technological challenge concerning the further development of OTEC is the construction of larger systems. In order for the process to work, a 100 MW plant would require pipes at least 10 m in diameter and 1000 m in length and be able to pump 750 tons of seawater per second. However, based on experience from the offshore oil industry, it should be possible to construct a 10 MW OTEC plant with today's technology. Two companies are currently planning the construction of such facilities: American defense, aerospace and technology company, Lockheed Martin, as well as the French naval and defense giant DCNS. Both systems are offshore floating systems and are to be located on the southern coast of China and near the French pacific island of Martinique respectively. The main reason that only so few plants have been built to date next to the technological challenge are the up-front costs required for construction. By using the multifunctionality of this process and implying a steep learning curve in the construction of larger OTEC plants this technology could become competitive in the mid to long term future (*155*).

2.3.3.2.6 Combined Ocean Energy

Despite the relatively low installed capacity of all the ocean energy systems mentioned above, the future will most likely see these technologies become mature and able to compete with other forms of power generation. For instance, the EU has stated in its Ocean Energy Roadmap the target for installed wave and tidal energy capacity by 2050 to be 188 GW, while by 2020 a mere 3.6 GW are to be installed. Thus, an immense acceleration of business is to be expected already before 2050 (*156*). Figure 2.41 shows different scenarios for this development depending on the speed technological progress and infrastructure development.

So far, all of these offshore energy generating technologies have only been tested as individual prototypes at different scales. The next step in floating renewable energy production will be cost reduction measures through learning effects and increasing size of the individual systems as well as in the longer term to build not only single devices but entire arrays potentially combining different power generation methods to harness the vast amounts of energy that are available on and in the ocean. An impression of such a floating combined wave and wind energy farm is shown in Figure 2.42.

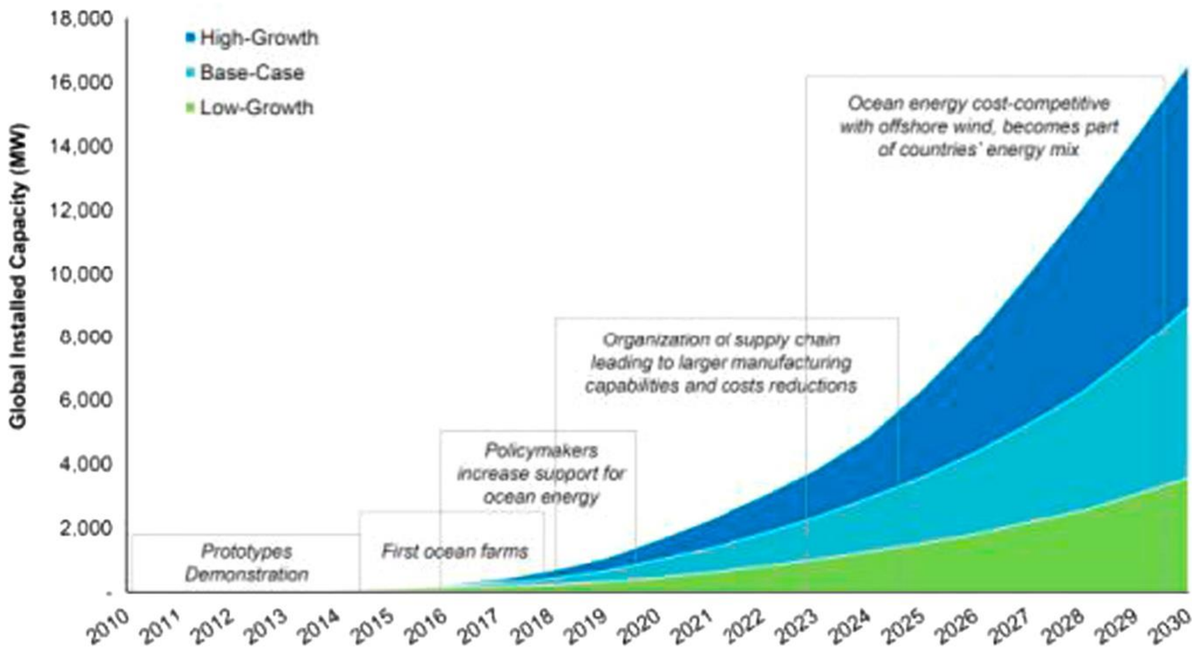

Figure 2.41: Forecast for global ocean energy development (157)

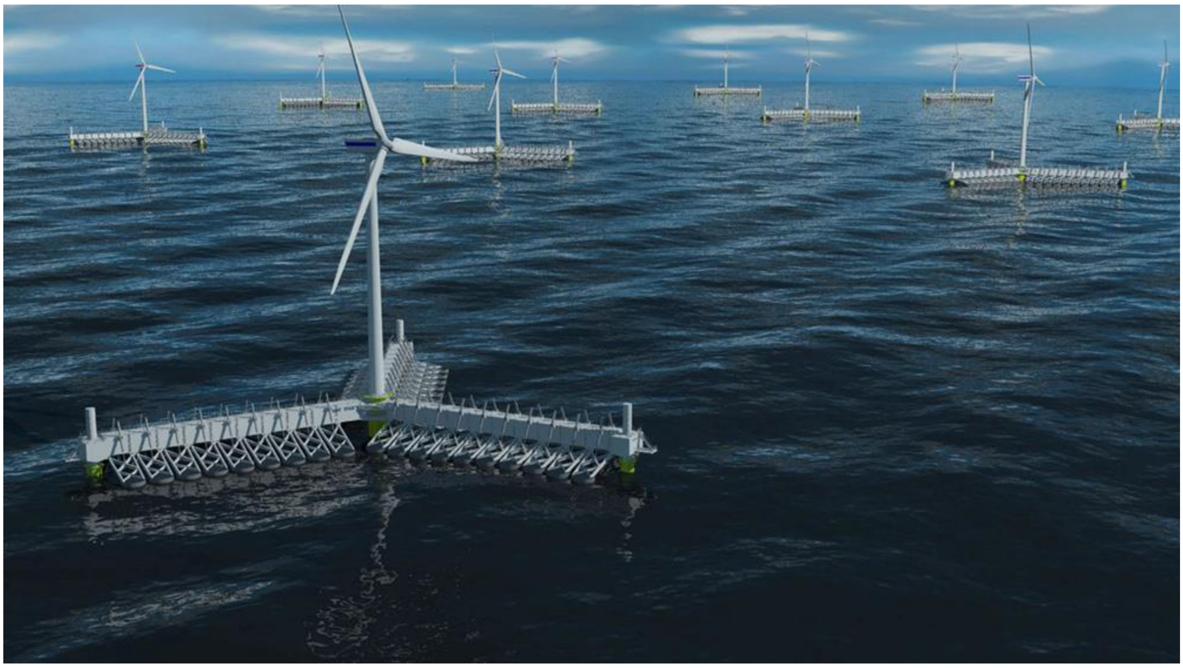

Figure 2.42: Future vision of a combined wind and wave energy farm offshore (75)

2.3.4 Food Production

As described in Chapter 2.2.2, the oceans will play an important role in feeding the growing world population in the future, with a promising step for increasing aquaculture production being the construction of industrial scale floating farms offshore (*94*). An example of such an endeavor is the establishment of Ocean Farming, a subsidiary of the Norwegian SalMar group. Ocean Farming is currently building a full-scale prototype of a semisubmersible off shore fish farm for the cultivation of salmon. The entire structure, which is shown in Figure 2.43, is 110 m in diameter, 68 m high and has a total cage volume of 250,000 m^3. The building in the middle of the structure will be used to store the fish feed and house the crew of 3-4 people required to monitor the operation. The entire installation is fully automated to enable all fish handling operations to be performed on board and to eliminate heavy manual operations (*103*).

Figure 2.43: Ocean Farming's semisubmersible offshore fish farm raised (top) and submerged (bottom)(103)

Despite the numerous opportunities for aquaculture in the future, a number of challenges will need to be addressed to achieve sufficient growth while remaining sustainable. The most promising approach to increasing efficiency is most likely the combination of different species ranging from plants to finfish in one system to create a more or less complete food chain. This newly emerging type of aquaculture system is termed "integrated aquaculture". The main idea of integrated aquaculture systems is to combine traditional aquaculture with hydroponics (the growth of plants in aqueous media) by using the waste produced by the cultivated fish to fuel the growth of plants, which can be harvested for human consumption or in turn provide a source of nutrients for the fish or other species in the system. In general such systems contain a species of fish or crustacean relying on feed, 1-2 species that extract particulate organic nutrients from the wastewater and one species (usually macro algae) that extracts dissolved inorganic nutrients such as nitrogen and phosphorous (Figure 2.44). The main economic and ecological advantage is that waste streams containing high amounts of nutrients are utilized for production of further biomass instead of being released into the environment leading to potential eutrophication and other environmental damage. Various combinations of species have already been tested and the results are very promising for large scale development. However, the combination of different species in one system increases the risk of diseases and further research in this area will be required to increase the economic viability of integrated aquaculture (*158*).

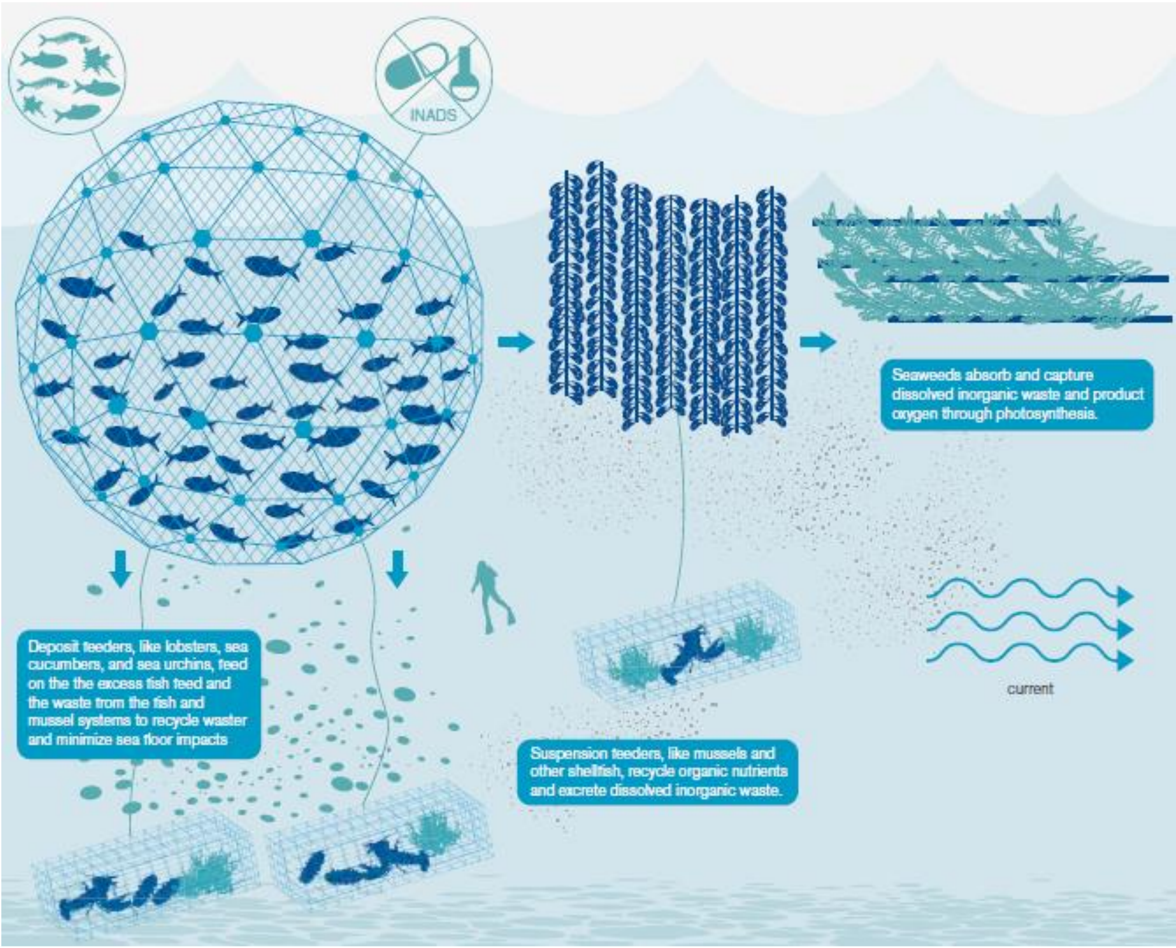

Figure 2.44: The concept of integrated aquaculture (159)

2.3.5 Transport

In an increasingly mobile and global society infrastructure enabling transport of people and goods is an essential component for economic productivity. A growing population requires more and larger transport infrastructure also adding to the issue of land scarcity for many regions. Consequently, moving infrastructure functions related to transport onto the water may serve to relieve pressure on available space on land.

2.3.5.1 Floating Roads and Bridges

Floating bridges have been constructed extensively in the past to connect urban centers across waterways which are too deep for the construction of a traditional bottom fixed bridge. The earliest floating bridges were basically wooden walkways built over a row of boats which were anchored to the sea floor and date back to as early as the 11^{th} century BC. These structures could not handle very heavy loads, had a very short lifespan and needed to be renewed on a regular basis. An example for such an early floating bridge is the Dongjin Bridge in China (Figure 2.45). It was constructed in the 12^{th} century AD and having been completely renewed regularly remains in operation to date. Despite the simplicity of this type of construction, the low durability and consequently high maintenance requirement lead to the development of an improved concept, the pontoon bridge. Pontoon bridges float on large, hollow concrete or steel pontoons that are connected to each other and the two opposing banks. The main advantage of floating bridges is that they are more economical than bottom fixed bridges at a certain depth and can be installed regardless of the composition of the bottom soil. Another advantage is, that many of these bridges have a mobile section to allow for water born traffic across the channel or lake as well. For example, the 410 m long Yumemai Bridge in Japan can rotate to allow larger ships to pass (Figure 2.45) (*63*). The world's longest floating bridge is currently the Evergreen Point Bridge in the USA. The original bridge was constructed in 1963 and had a total length of 4,750 meters with a 2,310 meter floating section consisting of 33 pontoons. Due to increased traffic and the poor condition of the bridge construction of a replacement bridge began in 2012. This replacement bridge opened in early 2016 has a 75+ year life expectancy and is built to withstand winds of up to 140 km/h (*160*). The cost estimate for construction was around $4.65 bil. (*161*). Looking at the image of this huge floating construction in Figure 2.45 it becomes apparent why it may be difficult to make a distinction between a floating road and bridge.

Figure 2.45: Floating Bridges, Dongjin Bridge in China (63) (top left), Yumemai Bridge in Japan (162) (top right), Evergreen Point Bridge USA (63) (bottom)

Floating bridges are also being considered for a number of future projects. For instance, in Norway the coastal highway E 39 is an 1100 km long route running along the western coast of the country. In total there are eight ferry connections along the route crossing wide and very deep fjords. Current travel time from one end (Kristiansand) to the other (Trondheim) is around 22 hours. In an effort to decrease this travel time to a total of around 13 house Norway's Ministry of Transportation and Communication commissioned a project to clarify the technological challenges and feasibility of replacing the ferry crossings by spanning structures. Due to the depth of the fjords which reach up to 1300 m the concept of floating bridges is considered very promising. Other concepts which are being reviewed for this $25 bil. project are submerged tunnels which are the topic of the next subchapter (*163*).

2.3.5.2 Floating Tunnels

Despite all their advantages, floating bridges are susceptible to high winds, which has been the major cause for failure in the past. Another concept to cross deep stretches of water which doesn't have this weakness is the submerged floating tunnel (SFT). An SFT is also called an Archimedes Bridge, as it floats beneath the water's surface using its buoyancy as a support. The idea is to place the tunnel at significant depth to allow water traffic to pass overhead, but not deep enough to require any specially precautions due to water pressure. The concrete tube of the tunnel can either be positively or negatively buoyant. A positively buoyant, floating tunnel could be held in place through anchoring to the seabed, while a negatively buoyant tunnel would need to be supported either by columns (similar to an underwater bridge), or by mooring to pontoons floating on the surface (Figure 2.46). Two concepts have been developed for the construction of a SFT. The first is to cast the concrete sections of the tunnel in a dry dock and seal the ends with a watertight membrane. The sections are then floated in to place and sunk. Once they are attached to each other, the membrane can be removed. The other option is to build the sections unsealed and pump the water out once they have been connected In addition to the already mentioned weather and earthquake resilience, the main advantage of SFTs is that the overall structural stability is independent of the structures total length since it is supported to a large extent by buoyancy forces. Furthermore, SFTs are invisible from the surface and thus preserves the natural look of the waterbodies they cross. Like floating bridges, SFTs may also be a cheaper alternative to the traditional way of crossing waterways, especially at large depth. The construction of an SFT has been proposed multiple times, dating as far back as the late 1800s. However, to date no SFT has actually been built. The main reason is that the concept has never been tried before and there is a large concern of losing the entire structure in case of a breach and consequent flooding. Through careful design of a positively buoyant tunnel, even in the case of flooding, this catastrophic event could however be avoided. Interest in SFT is growing and it is only a matter of time until the first consortium will find the courage to go ahead and begin construction (*164*).

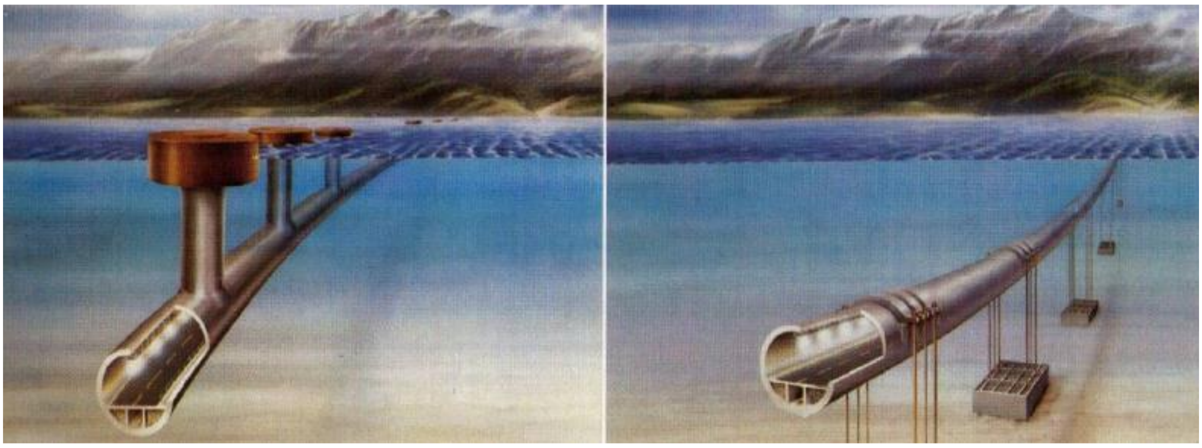

Figure 2.46: Concepts for submerged floating tunnels, attached to surface pontoons (left), anchored to the seabed (right) (165)

2.3.5.3 Floating Harbors and Docks

A logical application for floating construction is infrastructure which by definition is located adjacent to water such as docks and harbors for maritime transport. Floating docks are well known and have been constructed in various sizes ranging from smaller wooden structures to gigantic concrete pontoons for docking of container or cruise ships. The main advantage of floating docks is that they move together with the water level (for instance due to tidal action) and thus substantially improve conditions loading and unloading of vessels. Existing floating docks are all located near the shore. Examples are the container terminal in Valdez, USA or the pier in Ujina, Japan which are 230 m and 150 m in length respectively (*63*). With the increasing size and number of large containerships crossing the world’s oceans, existing harbors or under a constant pressure to grow and make room for higher capacity. This may involve dredging of existing waterways to make them deep enough for the draft of the growing container ships. With continued development of very large floating structures, it would be advantageous to construct new harbors further offshore in deeper waters. This would allow large ships to unload their cargo without having to navigate through narrow channels decreasing unloading and reloading times, thus increasing marine transport efficiency. Furthermore, this concept would also free up the waters further towards shore and inland for smaller more maneuverable vessels, which could transport goods closer to their final destination (*62*).

2.3.5.4 Floating Airports

Floating constructions have been proposed for expansions of multiple airports of larger cities located on the coast. This especially makes sense for the runways which take up a lot of space and cannot be used for any other function than the landing of planes. The first floating airport was proposed in 1973 for the Kansai International Airport in Japan. Although the proposal was not accepted, industry and academia had already begun research on the technology. In 1995, this research lead to the formation of the Technological Research Association of Megafloat (TRAM) an association of shipbuilders and steelmakers with the goal of further developing the technologies for ocean space utilization. Until 2001, TRAM conducted two major experiments in order to prove the technical feasibility of a floating airport based on the Megafloat concept depicted in Figure 2.47. For this concept, individual modules of the floating structure were to be constructed on land then floated to their final destination and connected at sea to form a large floating structure.

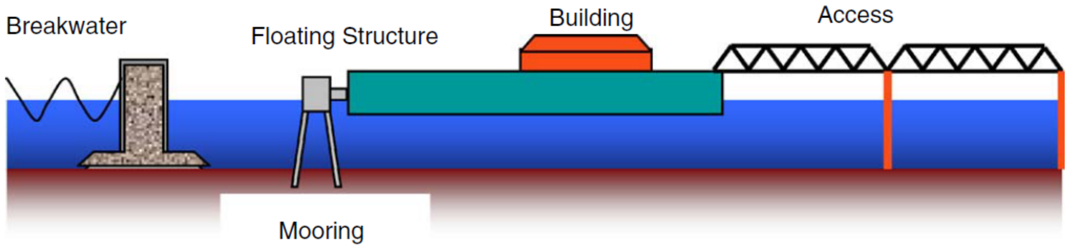

Figure 2.47: Megafloat concept for large floating structures near shore (166)

Phase 1, which took place from 1995-1997, involved the construction of a 300 x 60 m structure to investigate the basic technology for design, simulation, fabrication and joining at sea. In phase 2, a 1000 x 60 m floating runway was constructed from individual pontoon type modules and used for landing and take-off of smaller airplanes. Although it has been dismantled, the phase 2 runway remains the largest floating structure ever built to date. Information on the budgets and goals of the two project phases are shown in Table 2.8. The finished floating structures are shown in Figure 2.48 (*166*). The construction of a floating runway was later again proposed for the expansion of the airport in Tokyo Bay. Despite the overwhelming success of the phase 2 model the floating airport design was rejected in favor of land reclamation for constructing a new runway. To date no fully functioning floating airport has been built, however multiple proposals have been made for instance in San Diego or London. However, the high price (the estimated cost for the San Diego proposal was $20 bil.) and a lingering level of skepticism towards the technological feasibility, also lead to these concepts being rejected (*167*). Nevertheless, with today's technology it would be possible to construct a floating runway and with air traffic continuously increasing and space becoming more and more scarce it is only a matter of time before the first airports are expanded onto the water.

Table 2.8: Overview of Megafloat project phases (166)

	Phase1 (1995–1997)	Phase 2 (1998–2001)
Objective	Establish basic technology	Establish airport construction technology
Experiment	300-m-long model joining of units at sea	1000-m-long model joining of units at sea
Research	Design fabrication and joining at sea Operational requirement Environmental impact	Landing and take-off of airplane Concept study Legal aspect
Budget	$68.2 million	$103.6 million

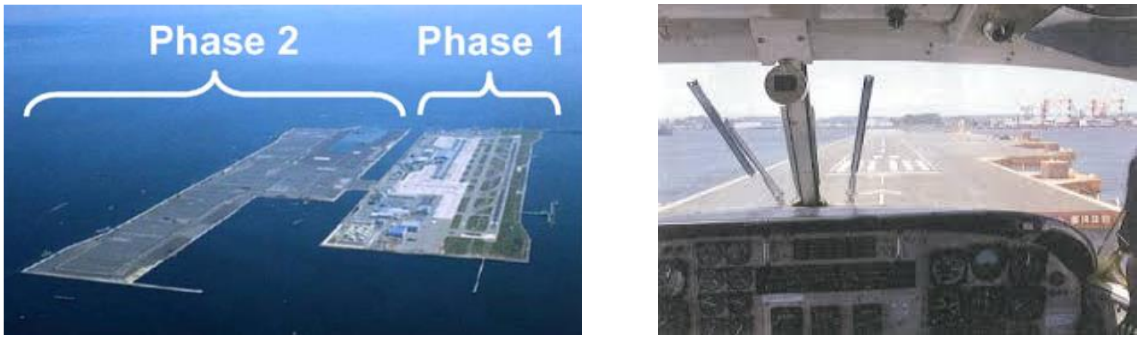

Figure 2.48: Finished structures of project Megafloat (166) (left), airplane landing during phase 2 tests (168) (right)

2.3.6 Housing and Recreational Space

2.3.6.1 Floating Buildings

Individual floating houses have existed since as early as the 16th century, with different tribes for instance in Cambodia, Vietnam or Peru living in small huts mounted on rafts. In the Netherlands, the traditional houseboats first appeared in the 17th century. The development of a practically unsinkable floating foundation made up of a concrete shell and a polystyrene core in the 1980s marked the beginning of modern construction of floating houses. Using this type of foundations, a number of smaller scale floating houses have since been constructed for instance in Canada, England or the Netherlands (Figure 2.49).

Figure 2.49: Floating homes in Victoria, Canada (left 169) and Delft, Netherlands (right)

Next to these smaller homes, larger buildings such as hotels, restaurants or offices have also been constructed on floating foundations. Examples can be found in the Netherlands, Hong Kong, Japan or Canada (Figure 2.50). Although various examples of floating buildings do exist, living on water is still a niche market and changes in policy, public perception, and time will be required for a larger commercial market to develop (*63, 127, 170*).

Figure 2.50: Larger floating buildings: The King Pacific Lodge in Vancouver (left 171), Jumbo Restaurant in Hong Kong (right 172)

2.3.6.2 Stadiums & Entertainment Facilities

A first step for the integration of floating construction into future city planning is to move buildings with lower economic functions out of city centers and onto the water. Such buildings include sport stadiums or other entertainment facilities which usually take up a lot of space. In land scarce Singapore and Japan this first step has already been taken with the so-called Float at Marina Bay. The Float is the world's first and currently only floating multipurpose stadium designed for sporting events and cultural performances. It consists of 15 modular steel pontoons are rigidly connected to form a stage measuring 120 m x 83 m. The size of the structure is large enough to enable soccer games to be played upon it (Figure 2.51) (*63*). To date no other large-scale facilities of this kind have been built. Various designs are however in the concept or planning stage and may become reality in the next decade.

Figure 2.51: The Float at Marina Bay, Singapore (63)

2.3.6.3 Parks and Recreational Areas

Another type of residential infrastructure which presents itself as an early option for floating construction are parks and residential areas. Since these areas do not contain massive buildings the platforms do not have to be as rigid and carry as much weight allowing for cheaper construction. One of the few existing examples are the Floating Islands of the Han River in Seoul, the Floating Pavilion in Rotterdam and a small facility along the shore of the river Seine in

Paris composed of five garden islands. However, many cities with large waterfronts are considering the construction of floating parks as new areas of recreation for the population. This includes for instance Rotterdam (*173*), Chicago (*174*), London (*175*) or Copenhagen (*176*).

2.3.7 Challenges Facing Large Scale Application

As can be seen from the previous subchapters, there exist a multitude of opportunities for the application of floating infrastructure. These different areas of application will involve various types and designs of floating structures depending on their specific requirements. This will also necessitate the use of a large amount of different construction materials in order to meet these requirements of individual components. The marine environment is one of the most hostile environments concerning material degradation due to corrosiveness, the occurrence of wetting and drying cycles, thriving biological activity and high loads from wind and waves (*177*). As local conditions vary from area to area and season to season, the accurate prediction of lifetimes for marine structures is very challenging (*178, 179*). One step towards improving the overall viability and also sustainability of floating infrastructure is the development of more accurate prediction models (*180*). In a further step, the use and development of environmentally friendly protection strategies for existing materials and the development of intrinsically more resistant materials will be of paramount importance for the widespread adoption of this construction approach. Furthermore, in order to focus, from the beginning, on developing sustainable and economically viable materials and solutions, the long-term availability of all required raw materials needs to be taken into consideration already today. Next to these material and engineering related challenges, another barrier to the large scale introduction of floating infrastructure is a lack of funding mainly due to the risk associated with the high installation costs and missing regulatory framework for such applications (*181*). Exploring legal and insurance aspects of floating structures in coastal areas as well as international waters will be necessary to increasing investments by governments and private companies. The existence of large floating oilrigs for offshore drilling, full scale prototypes of floating wind turbines and also multistory floating houses serves as a clear demonstration that the associated engineering challenges can be solved.

The main section of this thesis focuses on supporting the development of floating infrastructure by addressing the challenge of a systematic and targeted selection of materials and research and development approaches to enable a sustainable and cost-effective construction of various components. The following chapters will explain the framework and its applications in detail.

3 Development of Methodological Framework

A detailed description of the methodological framework is presented in this chapter and is structured as follows. First the overall scope of the framework is briefly described, as well as the points which differentiate it from existing material selection frameworks. Next, the evaluation and scoring methodology of the framework is explained along with a description of the process of identifying and selecting the necessary categories and attributes to cover all aspects of material performance. Chapter 3.3.2 and 3.3.3 then present a detailed description of all attributes and their individual scales which are based on data from recent literature and discussions with multiple industry experts. The multiple possibilities of applying the framework are shortly discussed in Chapter 3.3.4.4. These applications will be shown in more detail in the individual subsections of Chapter 5. The chapter concludes with a brief summary of the framework and its intended use.

3.1 Scope of Framework

As described in the Chapter 2.3, a central component enabling the widespread application off floating infrastructure, a promising climate change mitigation and also adaption strategy, are construction materials that are durable, economic to use, sustainable, safe and readily available in the long-term future. The identification and development of suitable material options therefore presents a first step towards large-scale global growth of this marine construction industry in the future.

However, the marine construction industry (regardless of the level of growth it may experience in the long term) represents only a portion of the general construction industry as a whole. Consequently, the entire industry has an overwhelming effect on the previously described environmental as well as social megatrends and in turn is also influenced by these developments. Therefore, not only providing optimal materials to enable the global growth of floating infrastructure, but also increasing the overall sustainability of the global construction industry in general forms an essential part of the solution to these issues. Consequently, the framework was created intentionally broad, in order to be applicable to many different types of materials and environments, not just the marine environment.

3.2 Material Selection in the Construction Industry

The construction industry and its supply chain are responsible for over 30% of global greenhouse gas emissions and 36% of global waste production which is estimated at 3.8 billion tons per year (*182, 183*). Decreasing global resources and noticeable impacts from climate change have strengthened public advocacy of environmental protection measures which are being more and more strictly enforced by governments around the world. As a major source of these impacts the construction industry is moving towards more sustainable construction strategies. An often thought out approach to such strategies is the systematic selection of optimal construction materials. Construction materials have a large effect on the overall sustainability of construction, as their physical and chemical properties largely determine the amount of material required for a certain structure, their lifetime in a given environment and the overall energy consumption during the use phase of the structure (*184*). Furthermore, embodied energy of construction materials, arising from their production and transport, can be responsible for 40-60% of the lifetime environmental impact of a structure (*185, 186*). Therefore, various fields of research are aiming to improve the sustainability of employed construction materials, for instance through the development of new processing techniques or alternative raw material compositions (*187–191*). Such research is highly capital intensive. As an example, the US Government funded various materials research programs with over 23 billion $ in 2014 (*192*). Furthermore, most projects require years to decades of experimentation and testing to generate significant, robust results. Additionally, the adoption of new materials and technologies in construction is relatively slow compared to other industries (*193–196*). Due to this long period between initiation of a research project and industrial application, and the limited funds available to research institutions and also companies, it is essential to evaluate and prioritize individual projects not only according to their potential to improve specific aspects of a material, but also according to the timeframe for which they will provide this benefit, depending on the used materials' future availability.

Existing prioritization frameworks do not take these context specific factors into account, as they are mostly focused on ranking research and development projects in a company setting (*197–200*). Furthermore, those frameworks which do cover research concerning construction and sustainability require detailed knowledge of individual projects to produce a ranking and thus cannot be used to identify new projects in the early stages of research planning (*201, 202*).

Therefore, the presented framework was designed to aid the process of identifying promising areas for research and development focusing on construction materials and prioritizing them according to their impact on the overall sustainability of the industry, as well as their potential for long-term commercial applicability. The framework is based on a holistic ranking of materials according to their technical, economic and environmental performance in a desired environment and for a wide range of specific applications or components. While there exist multiple frameworks for the ranking and selection of construction materials, they are mainly applicable to very specific material selection problems and also lack any consideration of long-term developments (*203–207*). In the light of increasing global scarcity of various materials as well as dwindling resource stocks it is however imperative that the long-term future availability of raw materials required for the production of construction materials be included in evaluation methods aiming to improve the sustainability of current construction practices (*208–210*). Therefore, the factors affecting the long-term availability of the raw materials required for production of each material are also assessed in the presented ranking. Thus, the framework evaluates each material's potential for long-term usage in construction, and, combined with the evaluation of material performance, identifies the areas where research funding has the highest probability of providing lasting improvements for the industry.

3.3 Framework for Holistic Ranking of Construction Materials

3.3.1 Ranking Methodology

In order to identify suitable research areas for the improvement of construction materials, the strengths and weaknesses of individual materials need to be evaluated. Thus, a holistic ranking of materials according to their technical, economic and ecological performance needs to be completed. This requires a great number of factors and aspects to be analyzed. As such, multi criteria decision analysis (MCDA) is employed (*211*). Specifically, a straight-forward simple additive weighting process is used to generate a single score for each material from multiple individual, property specific scores. This method is adapted for the presented framework by incorporating two hierarchical levels: categories and attributes. A category consists of multiple attributes. The attributes are the criteria that are evaluated and scored for each material. The stepwise process for applying this framework is shown in Figure 3.1 and will be shortly described.

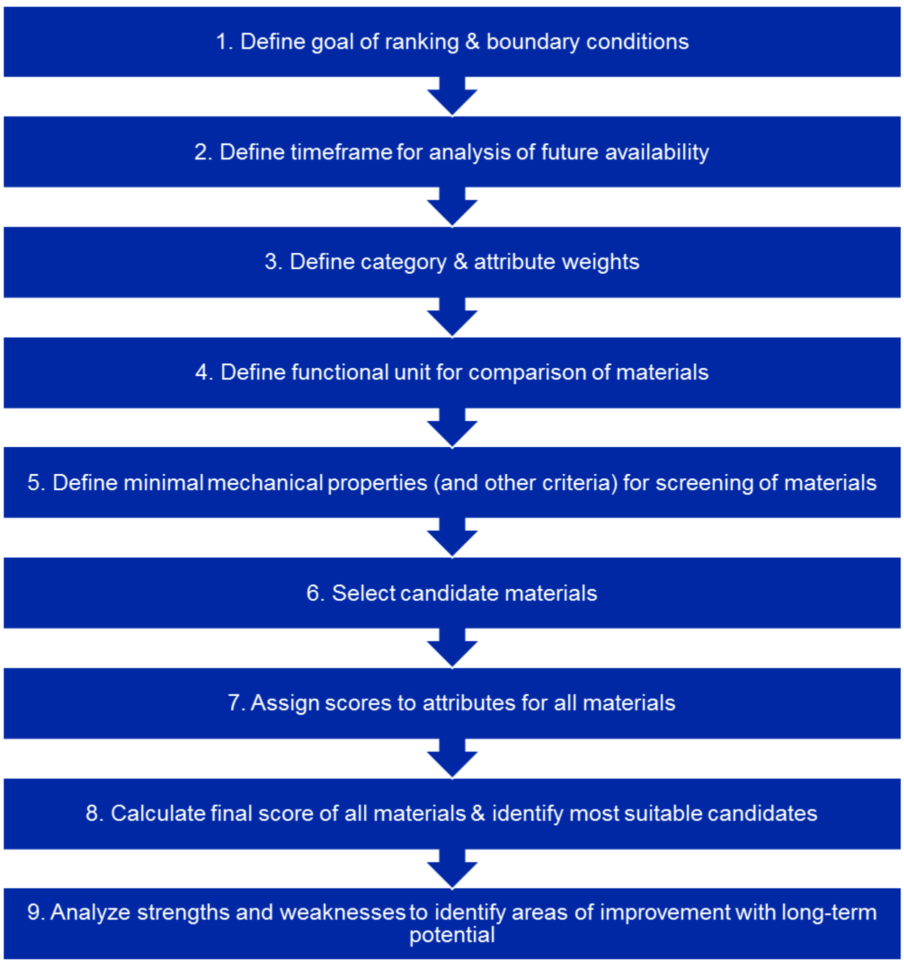

Figure 3.1: Methodology for application of framework to material selection.

The first step consists of defining *the goal of the ranking*. As a material's performance depends on the specific use case, different cases will produce different rankings. Therefore, it is essential to specify the boundary conditions and goal of the ranking to begin with. This includes, for instance, the definition of broad material categories which are to be analyzed and the environmental conditions for which their performance should be ranked. Furthermore, the *timeframe* for the analysis of future availability should be established. This timeframe should not be below 20-30 years as this would severely limit the evaluation of a materials long-term potential.

To adapt the ranking to the specified goal, each attribute and category has a corresponding *weighting factor*. Three possible values for the weighting factors are applied, depending on the importance of an attribute or category for the use of a material in the defined environment and application. Attributes with a high, medium or low importance are weighted with a factor of 3, 2, or 1 respectively. This method allows the weights of the different categories and attributes to be easily and quickly adapted to a variety of use cases and timeframes by increasing the weighting factors of essential attributes and decreasing those of less central attributes. Weighting factors can also be established with more sophisticated methods, such as the analytical hierarchy process (AHP), which however are substantially more time consuming.

In a next step a *functional unit* needs to be defined, which is in line with the specified goal. This allows the comparison of materials with widely diverging properties according to the defined performance requirement (ex. ability to carry a defined load). Additionally, according to the application and environment specified, minimal mechanical properties (ex. stiffness, compressive strength, etc.) can be defined in order to *screen materials* and reduce the number of candidate materials introduced into the final ranking (*211*).

The *scoring of the attributes* is then completed on a 5-point scale, 1 being the lowest and 5 the highest possible score. For each attribute, the values of 1, 3 and 5 were defined to represent the following scale:

1. Property or value below the level a material can be considered acceptable
3. Property or value that can be seen as average for a material used in construction
5. Property or value of a hypothetical ideal material

This scale allows not only the comparison of materials included in the ranking amongst each other, but also shows how far each individual material is from an ideal state for each attribute.

The attributes included in the framework are either qualitative or quantitative. For the quantitative attributes, values were specified for the points along the scale. For the qualitative attributes, the requirements for each of the three mentioned points were described as precisely as possible.

To *calculate the overall score* of a specific material the scores of all four major categories are calculated first. The category scores are computed by dividing the aggregated weighted attributes by the sum of the weighting factors:

$$C_j = \frac{\sum_{i=0}^{n} A_i \times a_i}{\sum_{i=0}^{n} a_i}$$

where C_j is the score of category *j*, A_i the score of attribute *i* and a_i the weighting factor of attribute *i*. These category scores in turn are weighted, aggregated and divided by the sum of the category weighting factors resulting in the final score for each material:

$$M = \frac{\sum_{j=0}^{n} C_j \times c_j}{\sum_{j=0}^{n} c_j}$$

where *M* is the final score for a specific material and c_j the weighting factor for category j. Following this process, the framework produces a final ranking of the selected materials related to the goal specified by the user. Each materials' score for the individual attributes thus highlights its strengths and weaknesses, while the category and final material scores identify the overall most promising materials for a given application.

3.3.2 Category and Attribute Selection for Framework

To develop a holistic ranking the selection of appropriate categories, attributes and scale values is critical. The categories need to cover all aspects relevant for the current and future use of materials in construction, while not being redundant. The same is true for the attributes contained in each category. Additionally, the attributes and corresponding ranking scales need to be general enough to be applied to a wide range of materials with different behaviors and properties, and at the same time specific enough to allow for a scoring process that is as exact and objective as possible.

In a first step a review of the literature was conducted to identify the attributes which were previously used in construction and engineering related MCDA material rankings and sustainability assessments (*203, 204, 211–224*). Although these frameworks are mostly case specific, attributes could be grouped into three major categories: technical performance, economics, and sustainability and environmental impact. Each category covers an area that is essential for the potential of a material to be used in sustainable construction.

The technical performance of a construction material is determined by two main factors; its mechanical properties and its durability. The mechanical properties of a material determine the way in which a structure can be designed with it and vice versa, meaning a specific structural design requires certain minimal mechanical properties for each of its components. As these properties, such as Young's modulus, tensile/compressive strength or fracture toughness, are precisely measurable, they can be used to define constraints for potential candidate materials (*211*). Consequently, mechanical properties are used for screening of candidate materials in this framework and are not included as an individual category.

Once a material meets the minimal mechanical requirements for a component in construction, the further technical performance is determined by the time the material retains these properties in a given environment; i.e. its durability. Durability is difficult to predict and is determined by a materials resistance to chemical and physical external influences or impacts such as corrosion or biological degradation. These impacts are highly dependent on specific environmental conditions. For individual construction environments, the detailed assessment of a material's durability provides information on the specific resistances which would need to be improved to increase the lifetime and therefore the technical performance of the material.

Thus, the combination of a material's mechanical properties and durability in the service environment determine how much material is required for a certain component and how long this will last. The smaller the amount of material necessary to fulfill a given function and the higher the durability of this material, the fewer resources (for production of the material itself, as well as materials and energy required for maintenance) will be required over the desired lifetime of the structure. Consequently, these properties indirectly influence the overall sustainability of using a given material for a specific application.

For the evaluation of the commercial potential of a certain material for use in the construction industry the costs involved with using the material also needs to be analyzed. This includes not only the actual lifecycle costs (from purchasing, construction and maintenance to disposal) but also the indirect costs associated with the various risks involved. Furthermore, a projection of the future price of the material is needed to assess its competitiveness in the long-term.

Next to the technical and economic potential, the assessment of the environmental impacts associated with the use of a given material is necessary to ensure that material developments not only aim to improve mechanical or physical properties, but also contribute to increasing the overall sustainability of the construction industry. For existing materials this provides crucial information on developments that are needed if continued large scale usage of the material is to be sustainable. For potential research and development projects, it enables a rough assessment of the sustainability of the proposed approach early in or even before the actual material development process.

These three categories evaluate the potential performance of a material in the present. However, in light of the increasing dynamics of global change, such as population growth and industrialization pushes (esp. in emerging countries), leading to an ever-increasing scarcity of various resources and materials, a consideration of future availability is essential for evaluating the long-term potential of a given material development project. If this is neglected, it may be the case that a new material, which at the beginning of development achieved a high score in all the previous categories, may become unsuitable for use in construction by the time it reaches the market, as certain raw materials employed in its production are no longer readily available or have become substantially more expensive. Thus, the evaluation of future availability allows an efficient distribution of resources to projects that have a high probability of long-term commercial applicability. Literature on criticality assessment was reviewed to identify the attributes required to cover this category (*48*, *225–230*).

In a final step, through discussions with experts from industry and academia, the previously identified attributes were adapted, and additional attributes were added to enable the coverage of all aspects necessary to achieve the goals intended for the presented framework. This resulted in the 4 categories and 27 attributes shown in Figure 3.2.

Durability	Economics	Sustainability & Environmental Impact	Future Availability
Corrosion Resistance	Material Costs	Raw Material Renewability	Short-Term Raw Material Availability
Moisture Resistance	Ease of Manufacture	Recycling Approach	Long-Term Raw Material Availability
Resistance to Biological Degradation	Maintenance Costs - Vulnerability	Environmental Impact of Production on Human Health	Geographic Distribution of Raw Material Reserves
Fatigue Resistance	Maintenance Costs - Repairability	Environmental Impact of Production on Ecosystems	Potential for Restrictive Government Regulations
Resistance to Stress Corrosion Cracking	Disposal/Recycling Costs	Environmental Impact of Production on Resources	Development of Recycling Infrastructure
UV Resistance	Reaction to Fire		Projected Growth of Competing Industries
	Resistance to Fire		Ease of Production Increase
	Performance Uncertainty		
	Projected Price Developments		

Figure 3.2: Categories and attributes for evaluation of construction materials

3.3.3 Attribute Scale Definitions

3.3.3.1 Durability

As mentioned, the attributes in this category rate the resistance of a material towards chemical, biological and physical external impacts which determines the overall lifetime of a component in a given environment. To be able to assess the durability ratings of all candidate materials correctly, a good understanding of the exact conditions of the specified construction environment is paramount. The scales for the rating of each attribute shown in Table 3.1 need to be applied with consideration of these conditions.

Table 3.1: Ranking scales of Durability attributes

Attribute	1	3	5
Corrosion Resistance	Structural damage to material (in form of defined component) from corrosion in given environment in under 10 years	Structural damage to material (in form of defined component) from corrosion in given environment in 50 – 75 years	Structural damage to material (in form of defined component) from corrosion in given environment after 100 years, or immune to corrosion
Moisture Resistance	Material is degraded by moisture and loses all mechanical strength for instance through leaching or swelling	Mechanical properties of material are reduced when it becomes saturated with moisture but stabilize at a certain point. This behavior is predictable and reversible	Mechanical properties of material are not affected by moisture absorption
Resistance to Biological Degradation	Material is highly susceptible to attack from organisms present in given environment and is fully degraded over time (loses mechanical strength)	Organisms present in given environment do not directly attack or degrade the material but can accelerate other degradation processes	Material is immune to degradation or accelerated degradation by organisms present in given environment
Fatigue Resistance	Material does not have a fatigue limit and also exhibits unpredictable fatigue behavior	Material has predictable fatigue behavior and a fatigue limit	Material is extremely resistant to fatigue thus this is not a concern for the design of structures
Resistance to Stress Corrosion Cracking	Material is very susceptible to stress corrosion cracking which leads to highly increased speed of degradation and loss of mechanical properties	Material may suffer from stress corrosion cracking after longer exposure to the defined environment. Degradation and loss of mechanical strength are moderatly accelerated	Material is immune to stress corrosion cracking
UV Resistance	Material is highly susceptible to damage from atmospheric UV radiation and is completely degraded over time	Surface layer of material is degraded by exposure to atmospheric UV radiation, but strength reduction is limited	Material is not affected by UV radiation

3.3.3.1.1 Corrosion Resistance

Corrosion is one of the main mechanisms of damage affecting massive amounts of infrastructure globally (*231, 232*). Therefore, the ability of a material to resist corrosive action either from the atmosphere, seawater or other sources (ex. deicing salts) is paramount for the durability of a structure and needs to be considered carefully.

The corrosion resistance required of the employed material will depend on the desired lifetime of the structure in the environment in which it is situated. Turning this relationship around it is possible to rate the corrosion resistance of a material according to its expected lifetime in a given environment. The minimal achievable lifetime considered was 10 years, as structures that deteriorate in a shorter time can be considered as a waste of resources. An average lifetime for most infrastructure is around 50 years, while long term infrastructure such as tunnels or bridges are built with lifetime requirements of 100 years and more (*178, 233*). Although the estimation of lifetime is somewhat imprecise, especially for lifetimes exceeding 50 years (*180*), this measure allows a quick assessment of a materials corrosion resistance by a person with a certain amount of experience in the use of a specific material without the need for complex modeling of corrosion processes. If necessary, the lifetimes assigned to the different scores can be adapted to evaluate more specific components with significantly different requirements.

3.3.3.1.2 Moisture Resistance

Infrastructure is inevitably exposed to varying levels of moisture ranging from differences in humidity to full wetting and drying cycles due to rain or tidal action for coastal and marine structures. The absorption of moisture can lead to a strong reduction of mechanical properties in certain materials or even full deterioration over time. Clearly the ideal material is not affected by moisture in anyway. However, for some materials the reduction in mechanical strength caused by full saturation with moisture is predictable and if the component is dried the mechanical properties return to their original values. For such materials it is possible to design components with desired strength under given conditions. If this is not possible a material must be protected from large variations in moisture or cannot be used in a variety of environments.

3.3.3.1.3 Resistance to Biological Degradation

Depending on the environment in which a material is employed it will be exposed to different sources of biological attack. Bacteria, insects, fungi and other organisms can feed on certain materials or produce and excrete substances which cause extensive damage, potentially leading to failure of a component. Ideally materials are not affected or attacked by biological sources. In some cases, the material itself is not directly attacked but the presence of specific organisms in combination with other external sources can accelerate degradation processes. An example for this behavior is the microbial introduced corrosion of metals where the presence of certain bacteria can alter the physico-chemical properties of the environment at the material's surface thus enabling or accelerating corrosion (*234*). As such processes are slower than direct degradation this was set as the neutral point along the scale from full immunity to high susceptibility to biological attack.

3.3.3.1.4 Fatigue Resistance

Dynamic loading, i.e. the exposure to fluctuating mechanical forces, can cause fatigue damage in certain materials which ultimately reduces their mechanical strength and may lead to failure at loads far below critical levels. Therefore, the fatigue resistance of construction materials needs to be carefully assessed during the design phase. The fatigue behavior of materials can be measured with so called stress cycle (S/N) or *Wöhler* curves. However, since the exact performance of a material depends strongly on the exact experimental parameters being used it is hard to compare *Wöhler* curves from different experiments (*235*). Therefore, a more widely applicable qualitative scale was used. For materials which are known to suffer from fatigue a predictable fatigue behavior can be used to specify the lifetime of a component under given dynamic loads. If a material has a fatigue limit any loads below this fatigue limit will never lead to failure. Thus, a material with a known fatigue limit can be designed for unlimited fatigue life by increasing the diameter or thickness of a component. Ideally however a structure can be designed with only the amount of material required to carry the maximal defined static load for a desired application and no additional resources need to be used to account for potential fatigue damage.

3.3.3.1.5 Resistance to Stress Corrosion Cracking

In this framework stress corrosion cracking is defined as the combined effect of mechanical stresses and chemical attack in the specified environment. This attribute is included since some materials' resistance to for instance moisture or corrosion damage is determined by the integrity of the surface layer. Small cracks which may occur due to mechanical loading can strongly decrease a materials resistance to environmental damage. Since it is impossible to specify quantifiable values for this attribute, due to the fact that a variety of different materials and damage mechanisms are covered, a qualitative ranking was seen as the only viable approach.

3.3.3.1.6 UV Resistance

Most large-scale structures will be exposed to atmospheric radiation, mostly UV rays stemming from the sun. Some materials can lose mechanical strength with prolonged exposure to UV radiation due to photo-oxidative cleaving of the chemical bonds in the surface layer. If the UV rays are only able to penetrate a short distance into the material, the reduction in strength of a component is limited. Thus, it is possible to use excess material to account for the expected reduction. If not, the material needs to be protected from UV rays since failure will definitely occur after a certain time. However, it must be considered that even limited UV radiation induced micro- or nanolesions at the surface of a material will have negative impacts on other durability attributes.

3.3.3.2 Economics

This category covers the lifecycle costs involved with using a specific material in construction as well as development of these costs in the longer term. These attributes cover the purchase of the material, the manufacture into various components, maintenance costs, risk related costs and final costs of disposal. Thus, the long-term economic sustainability of the materials is rated. Despite being a major cost factor for residential buildings, energy usage is not included in this framework, as these costs are mainly determined by the overall construction design and cannot be assessed on the material level. These scales of the economic attributes are shown in Table 3.2.

Table 3.2: Ranking scales of Economic attributes

Attribute	1	3	5
Material Costs	Material cost [$/FU] lie above the 80th percentile of all materials evaluated	Material cost [$/FU] lie in between the 60th and 40th percentile of all materials evaluated	Material cost [$/FU] lie in the 20th percentile of all materials evaluated
Ease of Manufacture	Material is very difficult to form into diverse shapes, can only be manufactured in a factory, requires specialized, expensive equipment and is limited to certain sizes and geometries	Material can be formed into almost any shape and size, with specialized equipment in a factory	Material can be formed into almost any shape and size, without expensive specialized equipment on site by less experienced personnel
Maintenance Cost - Vulnerability	Material is easily damaged and fractures propagate easily through the material	Either material is easily damaged but damage remains local or material is more difficult to damage but fractures propagate easily	Material is very difficult to damage and damage remains local
Maintenance Cost - Repairability	Material once damaged cannot be repaired but needs to be replaced completely	Material can be repaired on-site, but original mechanical properties or durability cannot be achieved.	Material can be easily repaired on-site by less experienced personnel without removal to restore original mechanical properties
Disposal & Recycling Costs	The disposal of material waste or scrap is done by specialized companies that charge a fee for the process	Material waste or scrap can be given away for free to a recycling company, or can be disposed of free of charge	Material waste or scrap has a significant value and can be sold to other industries or recycling companies
Reaction to Fire	Material burns readily and contributes to fire falling into class E & F according to EN-13501-1	Material falls into Class C according to EN-13501-1	Material is completely fireproof falling into class A1 & A2 according to EN-13501-1
Resistance to Fire	Material loses mechanical properties in fire rapidly due to increase in temperature (t < 30 min, softening or degradation) and strength loss is difficult to calculate as it burns irregularly	Mechanical properties of material decrease in fire due to decomposition of surface layer. Increasing the cross-section increases time to collapse. This process is accurately predictable	Mechanical properties of material are not affected by heat from fire and material is not degraded
Performance Uncertainty	Material has not yet been used in construction for the specified use and environment. A high risk is associated with using it for the first time	Material has been used for smaller scale applications in other industries in the specified environment.	Material has been extensively used for large scale structures in construction for the specified use and environment. Regulations and codes exist based on long term experience
Projected Price Developments	Price for material expected to increase by over 50% in the specified timeframe	No changes in price to be expected in in the specified timeframe	Price for material expected to decrease by over 50% in the specified timeframe

3.3.3.2.1 Material Costs

The costs considered here are those for purchasing of the construction material from a producer on the market. As materials from different chemical groups (ex. metals and plastics) have highly different properties, costs need to be measured relative to a FU which defines the desired performance of the materials. As there is no clear way to specify ideal or unacceptable costs the scores are based on the percentile in which a specific material lies amongst all materials evaluated. Thus, the ranking of a material is dependent on the other materials evaluated. If for a specific scenario it is clear at which level costs are acceptable and unacceptable, the scales can be changed to reflect these considerations

3.3.3.2.2 Ease of Manufacture

Ease of Manufacture scores the ability to manufacture a variety of components for use in construction from a material and also indirectly measures the costs associated with this process. These costs include cost of machinery, labor and transport to the construction site. In order to cover all these factors and a wide variety of potential applications, Ease of Manufacture is measured on a qualitative scale. If a material cannot be readily formed into different shapes then the range of applications for which it can be used is reduced, which reduces the score. Additionally, if the size of individual components is limited, joining will be necessary for the construction of large components, which is often done manually and increases the costs of construction (*212*). Joints furthermore can present structural weak points which can increase a structures vulnerability. Therefore, size limitations reduce a materials score. Finally, if specialized equipment or a well-trained workforce is required this will increase the costs for machinery and labor. Although fabrication in a factory may be cheaper for certain materials than on-site fabrication (especially in countries were labor costs are high) the transport costs for the larger and heavier prefabricated components will be higher. Therefore, the ability to shape a material into components of any shape and size in a factory was set as the middle point in the ranking scale. The ability to shape the material onsite is applicable to many parts of the world where large scale factories are not present. As these are the areas where most demand for construction is expected in the coming decades this property was set as the ideal case (*14*).

3.3.3.2.3 Maintenance Costs – Vulnerability, Repairability

As the detailed establishment of individual maintenance regimes is beyond the scope of this framework, the measure of maintenance cost is assessed qualitatively. Therefore, the measure was split into the two attributes; Vulnerability (i.e. how often maintenance needs to be completed) and Repairability (i.e. how much each act of maintenance costs on a relative scale).

Vulnerability is determined by the ease with which damage can be initiated through mechanical forces and the ease with which this damage can propagate through the material. The scales were defined by combining these two properties with the center being a material that is resistant in one area but not the other.

The location where repairs can be undertaken (i.e. ease of repair) and the extent to which original mechanical properties can be restored when repairs are completed, were combined to measure repairability. The costliest option involves removal of the entire component either for off-site repair in a factory or complete replacement. On the other hand, the quickest and most likely cheapest option is to repair damages, such as fractures, on-site. Ideally this can be done by unspecialized workers with standard equipment to the extent that the original mechanical properties are restored.

3.3.3.2.4 Disposal and Recycling Costs

As disposal and construction waste is one of the largest existing waste streams on a global level, the costs associated with the end-of-life processing of a material are an essential part of the overall life cycle costs (*236*). As the exact costs of disposal and recycling vary greatly from country to country depending on local laws and infrastructure this attribute is scored on a rather broad, qualitative scale. This scale ranges from expensive disposal (done by specialized companies which charge for service) through free disposal up to the ideal point where material scrap or waste has a value and can be sold.

3.3.3.2.5 Reaction & Resistance to Fire

The behavior of material in cases of fire was included in the economic category due to the consideration that this behavior determines how much material needs to be used, and how much additional money needs to be spent on fire protection and prevention systems as well as insurances in order to meet applicable fire safety codes. This behavior can be measured by two different attributes: The reaction of a material to fire (i.e. its flammability behavior and tendency to start a fire) and the resistance of the material to fire and heat (i.e. how long it can retain its mechanical properties in the heat of an already existing fire) (*237*).

Concerning fire reaction, there exists European fire reaction classification system (EN-13501-1) which assigns one of the following 7 classes of fire reaction to construction materials based on a number of tests: A1 – no contribution to fire growth at any stage; A2 – no significant contribution to fire growth; B – very limited contribution to fire growth; C – limited contribution to flashover; D – contribution to flashover; E – significant contribution to flashover, and

F – products for which there is no data, or products failing to achieve class E (*237*, *238*). The class in which a material falls, determines the application for which it can be used in accordance with further European regulations. As classes A1 and A2 describe non-combustible products they were set as the highest value in this framework. Materials falling in classes E & F can be considered unacceptable, as costly, additional protection methods need to be implemented to ensure the fire safety of a structure.

Fire resistance is measured in this framework as a combination of a materials ability to retain its mechanical strength during a fire and the predictability of strength loss if it should occur. A standard fire reaches temperatures of 1000 °C after 60 min (*239*). Ideally a material will not be affected by these temperatures and retain its full mechanical properties indefinitely in a fire. The worst case is represented by a material that losses all mechanical strength in a fire in a short period of time regardless of its shape and burns at an unpredictable rate. Such a material will require extensive additional fire protection measures for instance through coatings or sprinkler systems to comply with fire regulations. Due to the unpredictability of the combustion process the use of the material will also involve higher risks and thus higher insurance costs. In between these two extremes is a material which losses mechanical strength at a predictable rate in a fire through degradation of its surface layer. Thus, it is possible to increase the time in which a component made from this material retains a minimum level of strength in a fire by increasing the cross section of the component.

3.3.3.2.6 Performance Uncertainty

When evaluating the potential for use in construction, a material's stage of development and level of industry adoption must be considered. For instance, for materials which have just left the development stage little experience exists for the use in specific environments. Such materials may have improved properties, however due to a lack of established codes or regulations the risks associated with their use in construction can be relatively high. This increased risk translates into increased costs incurred, for instance, through higher interest rates on borrowed capital or higher insurance costs.

3.3.3.2.7 Predicted Price Developments

All previous attributes are related to the performance of a material in the present. However, to assess the economic sustainability of using a material in construction the long term, price developments need to be considered as well, since this will influence the future usage of the material. Price predictions are surrounded with a high amount of uncertainty and this uncertainty increases in line with the prediction horizon. Nevertheless, it is possible to estimate the direction and magnitude of change to a certain degree. Changes in the range of 50% from today's levels were set as the two end points of the scale as changes exceeding these levels would have a significant impact on material usage in construction (*240*).

3.3.3.3 Sustainability & Environmental Impact

To assess the sustainability associated with using a material for construction two factors are essential. First, the direct impacts (emissions, land degradation, acidification etc.) caused by the production of the material, and second, the indirect impact this has on future generations' ability to produce and use the material due to depletion of the resource base required for its production. In the sustainability assessment of this framework the use phase is not included, since impacts occurring during this phase are only marginally dependent on the material, with specific design options and use cases as the major influences. All scales are shown in Table 3.3.

Table 3.3: Ranking scales of Sustainability & Environmental Impact attributes

Attribute	1	3	5
Raw Material Renewability	0 - <25% of raw materials are renewable	50 - <75% of raw materials are renewable	100% of raw materials are renewable
Recycling Approach	Material has very low recycling rates in construction leading to most demolition waste being brought to landfill or being incinerated	Material when used in construction is mostly downcycled into material that can be further used in the construction industry	Material can be recycled to use instead of virgin material and has very high recycling rates when used in construction
Environmental Impact of Production on Human Health	ReCiPe Endpoint impact score [EIP/FU] of material production on human health above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on human health in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on human health in 20th percentile of all materials evaluated
Environmental Impact of Production on Ecosystems	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems in 20th percentile of all materials evaluated
Environmental Impact of Production on Resources	ReCiPe Endpoint impact score [EIP/FU] of material production on resources above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on resources in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on resources in 20th percentile of all materials evaluated

3.3.3.3.1 Raw Material Renewability

The renewability of a material is essential for determining its overall sustainability as the resource base of renewable materials is at least theoretically unlimited in the long term. Thus, producing the material today will not have an effect on future generations' ability to produce the same material. Renewability of a material is measured in this framework by the proportion of raw materials required for production which can be considered renewable. Even if a material achieves a good score for this attribute, it is essential to look at the actual supply chain in detail, to determine whether a material is produced not only from renewable but also sustainable sources (See section 3.3.3.3.3).

3.3.3.3.2 Recycling Approach

Concerning disposal, the main factor influencing the sustainability of a material is the extent to which waste can be reintroduced into the material production cycle thus extending the resource base to recycled stock and eliminating the need for additional raw material extraction and the associated impacts. The recycling potential of a material is determined by the chemical composition and structure as well as existing recycling infrastructure. In this framework Recycling Approach is rated according to the way in which a material is disposed of or recycled at the end-of-life when it is used in construction. The worst option in this respect is disposal by landfilling or incineration, as the raw materials used for production of the material are usually unrecoverable. To date a growing amount of construction waste is downcycled (esp. in Europe) meaning that the material is reused in a different function with a lower value than the original virgin material (*241*). This point was set as the middle of the rating scale. The ideal case is full recycling where the raw materials of a material can be separated and re-introduced into the production process to substitute virgin raw materials thus reducing the pressure on resources.

3.3.3.3.3 Environmental Impact of Production – Human Health, Ecosystems, Resources

In this framework the full environmental impact of production is considered by conducting an LCA of the evaluated materials. The scope of this LCA ranges from raw material extraction until production of the final construction material (cradle-to-gate). The environmental impact of production can be calculated using for instance the ecoinvent database and a compatible program such as SimaPro (*242*). An internationally accepted calculation method is the ReCiPe method, which calculates a single endpoint score from all defined inputs and outputs of the LCA thus combining a multitude of existing metrics (ex. energy usage, greenhouse gas emissions, resource depletion, eutrophication potential). This endpoint score is composed of the three individual scores for impact on human health, ecosystems and resources (*243*). As impact scores are intended to be used for comparison and have no absolute meaning the proposed ranking scale is the same as for the costs, with materials being ranked according to the percentile in which their impact scores lie after all materials have been evaluated. To make these impact scores comparable they have to be calculated relative to the defined FU.

3.3.3.4 Future Availability

Availability is determined by supply and demand. Therefore, this category contains attributes determining supply and demand of the material itself as well as the raw materials required for its production. For all attributes, except those measured quantitatively (availability of raw materials and geographic distribution), the timeframe for which predictions need to be made is defined by the user in the first step of the framework.

Regardless of their total content in the final material, all raw materials are essential for its production. Therefore, for the rating of the future availability attributes, each attribute needs to be evaluated for all raw materials present in a respective material. The final score for the material is equivalent to the lowest score of the evaluated raw materials (i.e. the bottleneck). The scales for the future availability attributes are shown in Table 3.4.

Table 3.4: Ranking scales for Future Availability attributes

Attribute	1	3	5
Short Term Availability of Raw Materials	Raw material reserves/production ratio below 25 years	Raw material reserves/production ratio between 50-75 years	Supply large to unlimited so that data on reserves is not exactly available or reserves to production ratio over 100 years
Long Term Availability of Raw Materials	Raw material resources/production ratio below 50 years	Raw material resources/production ratio between 100-125 years	Supply large to unlimited so that data on resources is not exactly available or resources/production ratio over 150 years
Geographic Distribution of Reserves	Herfindahl-Hirschmann-Index of raw material reserves larger than 2500	Herfindahl-Hirschmann-Index of raw material reserves from 2150-1850	Herfindahl-Hirschmann-Index of raw material reserves below 1500
Potential for Restrictive Government Regulation	Regulations limiting the supply of raw materials will be implemented in the near future or are already in place and strongly limit the availability of raw materials	Uncertain whether regulations limiting access to raw materials will be implemented in the specified timeframe, but the possibility exists.	No realistic reason for governments to regulate usage of material or raw material in the specified timeframe
Development of Recycling Infrastructure	Recycling infrastructure will not develop significantly in the specified timeframe, leaving landfilling or incineration as the main disposal option for material	Recycling infrastructure will develop, increasing recycling rates. However, downcycling is expected to remain the only viable option.	Infrastructure will develop strongly in the specified timeframe, leading to high recycling rates (> 75 %) of material that can replace virgin material or recycling rate is already at this level today
Projected Growth of Competing Industries	Construction is only responsible for a small share of material's total demand and demand from competing industries is expected to exceed current supply levels in the specified timeframe	Along with other industries the construction industry is a major consumer of the material. As demand increases it is possible that competition for resources between these industries increases	The construction industry is the largest driver of demand for the material and demand from competing industries will become/remain insignificant compared to supply levels in the specified timeframe
Ease of Production Increase	Increase in production would require extensive investments into new facilities and the development of new production or manufacturing technologies	Increasing production would require new facilities or adaptation/expansion of existing facilities with mature technologies	Production could be significantly increased with existing infrastructure (mining, processing facilities etc.)

3.3.3.4.1 Availability of Raw Materials – Short-term, Long-term

Although there is much debate on the use of reserve and resource measures for the prediction of material availability (*226*, *228*, *229*, *244*, *245*) no better quantitative measure has been proposed in literature to date. Therefore, the future availability is measured by the reserve to production and resource to production ratios of the respective material's raw materials. The data on global production levels, reserve and resource bases can be obtained via the U.S. Geological Service (USGS) or industry specific sources (*246*). The definitions for reserves and resources can be described as follows: Reserves are mineral deposits that have been more precisely defined in terms of mineral content and that can be economically extracted using todays technologies. Resources are known mineral deposits that have yet to be fully characterized, or that present technical difficulties or are uneconomic to extract (*246*). The issue with these measures is that the reserves are highly dependent on current market prices and technologies. Therefore, if the reserves are used up, the price of the commodity will rise, and thus new resources will be turned into reserves extending the "lifetime" of the raw material. Consequently, two separate availability attributes are incorporated into this framework. The assessment of availability via the reserves/production ratio presents a more short term evaluation, since today's price levels and technologies are considered, while the resource/production ratio measures availability in the longer term as it allows for price changes and technological developments (*208*). This is also the reason for the different time values assigned for the specific scores.

3.3.3.4.2 Geographic Distribution of Reserves

From a political perspective supply can be influenced by export restrictions and unrest or conflict in producing countries (*48, 228*). These risks are exceptionally high, when existing material reserves are highly concentrated in a small number of countries. As in the Report on Critical Raw Materials for the EU, concentration is measured in this framework through the Herfindahl-Hirschman-Index (HHI) (*48*, *247*). The index can be calculated for each raw material using country specific reserve data obtained for instance from the USGS or industry sources (*246*). The score values are based on the assessment by the U.S. Department of Justice which considers a market with an HHI of less than 1,500 to be a competitive marketplace, an HHI of 1,500 to 2,500 to be a moderately concentrated marketplace, and an HHI of 2,500 or greater to be a highly concentrated marketplace (*248*). To keep the number of attributes which need to be assessed manageable, there is no distinction made between the supply risk due to possible export restrictions and political instability or a lack of governance in the producing countries. A high concentration is assumed to be representative of a high risk for the none-producing countries.

3.3.3.4.3 Potential for Restrictive Government Regulation

Government regulations aiming at reducing environmental impacts or stabilizing local economies can affect the demand for certain production practices or also uses of materials. Thus, even if resources would be available it may not be legal to use, produce or purchase a certain material. As the exact effect of government regulations on raw material availability is difficult to quantify this attribute is qualitatively measured according to the probability of regulations being implemented and the extent to which these regulations limit the availability of a specific raw material. Regulations to be considered can range from tariffs that raise prices, through export restrictions to bans and prohibitions.

3.3.3.4.4 Development of Recycling Infrastructure

The supply of raw materials is not only determined by the reserves and resources which are available for exploitation but also by the level of recycling enabling substitution of virgin material with existing material stocks. The future development of recycling infrastructure is measured in the same way and along the same scale as the Recycling Approach of a material in the Economics category. However, in this case, level and type of disposal/recycling which is projected to be achieved in the specified timeframe is relevant. Increases in recycling levels can occur due to new technological developments enabling a better separation of raw materials or simply through changing policies and practices which improve the recycling system. Materials which already today have high recycling levels can be assumed to remain at such high levels.

3.3.3.4.5 Projected Growth of Competing Industries

In order to fully assess the future availability of a material for the construction industry, expected demand from other industries needs to be taken into account as well. As a scenario-based assessment of the projected developments of all demand side industries is beyond the scope intended for this framework, the scale for this attribute is described qualitatively. In a first step, the competing industries for all raw materials of the evaluated material and the material itself need to be identified. Market reports on these industries as well as scientific papers on demand projections for individual raw materials can be used to assess how future demand from these individual industries compares to current and predicted supply levels. Next to the comparison of this demand and supply the position of the construction industry among the consuming industries needs to be assessed, as a stronger position of an individual industry (i.e. responsible for majority of demand) will ensure better access to scarce raw materials (*249*).

3.3.3.4.6 Ease of Production Increase

If a certain material is seen to be superior to others for the use in construction (be that due to economic, environmental or availability considerations) it may be the case that demand levels increase rapidly in short period of time. Therefore, it is essential to evaluate how a significantly higher demand level could be met in the future. The rating is based on the amount of time and capital which would be required to increase the production of the evaluated material to multiples of today's levels. This is determined by the overcapacities that are currently present in the industry and the maturity of the raw material acquisition and material production technology. Mature industries with high levels of overcapacities could quickly react to increasing demand simply by ramping up production in existing facilities or by reopening facilities that were shut down due to cost reasons. Mature industries without overcapacities would be able to meet demand by increasing production capacity with new facilities and raw material acquisition operations. Despite the fact that this would require significant investments the risks associated with these are known and clearly calculable due to the maturity of the technologies. Finally, the largest barrier to increasing production to global levels is faced by new materials that are currently only produced in small amounts in specialized markets. If increasing production requires a scale-up of the manufacturing process significant investments will be required. The development of such new technologies is also surrounded with a high level of mostly unquantifiable risk.

3.3.4 Application of Framework

There are multiple possibilities for applying the presented framework. The most basic application is the evaluation of existing materials, which have been readily adopted by the construction industry, according to their performance in relation to a defined use case. The resulting ranking identifies those materials which are most promising and at the same time allows a comparison of the tradeoffs involved in choosing one over the other. A first prioritization of research and development areas can be done by analyzing the weighting factors of the low scoring attributes of highly ranked materials. Focusing on improving attributes that are considered more important for the defined application will consequently provide the most value to the industry. As future availability is also evaluated it can be clearly analyzed whether a specific material will also in the future have a high economic potential. Thus, the previously identified research areas can be evaluated according to their long-term potential as well.

It is also possible to introduce newly developed materials into the ranking and compare them with the more established construction materials. Such an evaluation can demonstrate whether a material, which was developed for a specific purpose, is technically, economically, or environmentally superior to existing materials or if certain aspects need to be further improved before it can compete with them.

Finally, the same can be done at the beginning of a material development project. This can for instance be a project that was set up after analyzing existing materials' weaknesses. Even though the properties of the final material need to be estimated (as it doesn't exist yet), the framework requires the detailed evaluation of the future availability of all constituents employed in the planned production process. Thus, it is possible to gauge early on if the developed material will be usable on a global scale in the long term future, giving a clear picture on whether it is economically sensible to invest extensive funds in the material's development.

Next to material development the ranking provided by the framework also serves to identify policy measures which contribute to increasing the sustainability of construction practices. For instance, if a material is currently disposed of mainly via landfill, despite there being a better option (for instance downcycling) the result will be a high discrepancy between the "Recycling Approach" and "Development of Recycling Infrastructure" scores. This clearly indicates that policies aimed at educating users about the improved process are required to increase the materials end-of-life recycling rate. Another example is a newly developed material with an improved "Durability" and/or "Sustainability" rating but a lower "Performance Uncertainty" score. This demonstrates that extensive effort by governments or other institutions will be required to overcome the regulative and risk related barriers to enable the material's adoption in the construction industry.

3.4 Summary of Material Selection Framework

The development of improved materials is an essential strategy for increasing the sustainability of global construction practices. The sheer number of existing materials along with the variety of areas and approaches available for their improvement, lead to a plethora of potential research and development projects. To ensure an effective distribution of resources to projects with not only a high, but also long-lasting impact on the construction industry, it is necessary to carefully evaluate and prioritize the individual projects. The presented framework enables the identification and first, high level prioritization of such projects by evaluating their potential impact on a defined area of construction as well as their long-term commercial potential. This is achieved through a holistic ranking of individual materials' potential for long-term usage in construction, according to their technical, economic and environmental performance as well as the future availability of their raw material constituents. To cover all these evaluation parameters, the framework consists of 27 attributes divided into four categories. For each attribute a scale from 1-5 (1 being the lowest and 5 the highest possible score) is precisely defined either quantitatively or qualitatively. As each material is scored for each attribute, the framework provides an overview of each material's specific areas of strengths and weaknesses, which can be used to identify and evaluate potential improvement approaches. Next to the identification and prioritization of potential research directions, the framework enables a comparison of the performance of newly developed materials or planned material developments with existing materials established in the industry.

The framework, however, also has a number of shortcomings. First of all, despite being defined as clearly as possible, the assessment of qualitative attributes remains partly subjective (*211*). Therefore, it is essential to consult different sources of information (experts or literature reports) and discuss diverging opinions before establishing a final score (*217*). Second, the level of specificity with which use cases can be defined is limited, as the attributes are measured on a broad scale, in order to enable a comparison of completely different material types. For specific material selection problems more appropriate, and precisely measurable attributes need to be defined. Furthermore, for immediate construction in the present an analysis of future developments is superfluous. Finally, the framework does not provide information on the feasibility and exact cost calculations of specific projects. A more detailed evaluation of identified projects or policies needs to be conducted before funds are actually committed.

4 Application of Framework to Marine Construction

As mentioned before, the demand for resilient infrastructure located in marine environments is expected to increase in the coming decade as rapid urbanization of coastal areas continues and industries such as oil and gas, renewable energy generation or aquaculture move further off-shore to utilize the extensive amount of resources and space available on the open ocean.

Thus, the applicability of the framework described in the last chapter was demonstrated by focusing on the specific field of marine construction.

This chapter discusses the adaptions that were made to the original framework to allow an accurate evaluation of the performance of different materials when used in marine construction.

The first subchapter defines the overall goal of the entire ranking including the timeframe chosen for the different analyses of future availability. This is followed by the adaption of the individual attributes and scales to the marine environment as well as the weighting of the categories and attributes. Chapter 4.3 describes the material selection process and provides an overview of all the materials incorporated in the ranking. The final subchapter describes the data collection procedure used to generate the results of this thesis.

For each application to a single material category, a specific goal was stated, and a different FU was defined. Theses aspects are described in the respective results sections in Chapter 5.

4.1 Overarching Goal of Ranking

The overarching goal of the rankings generated in this work is to identify those structural construction materials that are most suitable for the sustainable use in marine construction in the long-term future. The performance of the individual materials is ranked for the isolated material without the consideration of any additional protection methods such as coatings. The *timeframe* for the predictions made in the analysis of future availability is 50 years. As a consequence of the long-term focus of this study the Disposal and Recycling Costs attribute in the Economics category was left out of the ranking. These costs are greatly dependent on country and process specific factors and therefore it is highly uncertain which value is actually appropriate (*250*).

4.2 Categories, Attributes and Weights

4.2.1 Adaption of Attributes

As the ranking is to be completed for the materials use in marine construction, the attributes were adapted to this specific case. This mainly affected the individual Durability attributes developed in the original framework which need to be changed to measure material performance in a general marine environment. The Durability of the evaluated materials was assessed for exposure in the splash zone, as this is the most aggressive location (*178, 251*). This adaption led to the scales and attributes shown in Tables 4.1-4.4 (Only the Durability and Future Availability attributes changed).

Table 4.1: Ranking scales of Durability attributes for marine construction case

Attribute	1	3	5
Corrosion Resistance	Structural damage to material from corrosion in less than 10 years in splash zone in average ocean water	No structural damage to material after 50-75 years in splash zone in average ocean water	No structural damage to material from corrosion after 100 years in splash zone in average ocean water
Resistance to Biological Degradation	Material is highly susceptible to attack from marine organisms and is fully degraded over time (loses mechanical strength)	Marine organisms do not directly attack or degrade the material but can accelerate other degradation processes	Material is immune to degradation or accelerated degradation by marine organisms
Fatigue Resistance	Material does not have a fatigue limit and also exhibits unpredictable fatigue behavior	Material has predictable fatigue behavior and a fatigue limit	Material is extremely resistant to fatigue thus this is not a concern for the design of structures
Resistance to Stress Corrosion Cracking	Material is very susceptible to stress corrosion cracking which leads to highly increased speed of degradation and loss of mechanical properties	Material may suffer from stress corrosion cracking after longer exposure to salt water and higher wave & wind forces (storm levels)	Material is immune to stress corrosion cracking
UV Resistance	Material is highly susceptible to damage from atmospheric UV radiation and is completely degraded over time	Surface layer of material is degraded by exposure to atmospheric UV radiation, but strength reduction is limited	Material is not affected by UV radiation
Moisture Resistance	Material is degraded by moisture and loses all mechanical strength for instance through leaching or swelling	Mechanical properties of material are reduced when it becomes saturated with moisture but stabilize at a certain point. This behavior is predictable and reversible	Mechanical properties of material are not affected by moisture absorption

Table 4.2: Ranking scales of Economic attributes for marine construction case

Attribute	1	3	5
Material Costs	Material cost [$/FU] lie above the 80th percentile of all materials evaluated	Material cost [$/FU] lie in between the 60th and 40th percentile of all materials evaluated	Material cost [$/FU] lie in the 20th percentile of all materials evaluated
Ease of Manufacture	Material is very difficult to form into diverse shapes, can only be manufactured in a factory, requires specialized, expensive equipment and is limited to certain sizes and geometries	Material can be formed into almost any shape and size, with specialized equipment in a factory	Material can be formed into almost any shape, without expensive specialized equipment on site by less experienced personnel
Maintenance Cost - Vulnerability	Material is easily damaged and fractures propagate easily through the material	Either material is easily damaged but damage remains local or material is more difficult to damage but fractures propagate easily	Material is very difficult to damage and damage remains local and does not spread easily
Maintenance Cost - Repairability	Material once damaged cannot be repaired but needs to be replaced completely	Material can be repaired on-site, but original mechanical properties or durability cannot be achieved	Material can be easily repaired on-site by less experienced personnel without removal to restore original mechanical properties
Disposal & Recycling Costs	The disposal (landfill or incineration) of material waste or scrap is done by specialized companies that charge a fee for the process	Material waste or scrap can be given away for free to a recycling company, or can be disposed of free of charge	Material waste or scrap has a significant value and can be sold to other industries or recycling companies
Reaction to Fire	Material burns readily and contributes to fire falling into class E & F according to EN-13501-1	Material falls into Class C according to EN-13501-1	Material is completely fireproof falling into class A1 & A2 according to EN-13501-1
Resistance to Fire	Material losses mechanical properties in fire rapidly due to increase in temperature (t < 30 min, softening or degradation) and strength loss is difficult to calculate as it burns irregularly	Mechanical properties of material decrease in fire due to decomposition of surface layer. Increasing the cross-section increases time to collapse. This process is accurately predictable through calculations	Mechanical properties of material are not affected by heat from fire and material is not degraded
Performance Uncertainty	Material has not yet been used in construction for the specified use and environment. A high risk is associated with using it for the first time	Material has been used for smaller scale applications in other industries in the specified environment	Material has been extensively used for large scale structures in construction for the specified use and environment. Regulations and codes exist based on long term experience
Projected Price Developments	Price for material expected to increase by over 100% in the foreseeable future	No changes in price to be expected in the foreseeable future	Price for material expected to decrease by over 100% in the foreseeable future

Table 4.3: Ranking scales of Sustainability & Environmental Impact attributes for marine construction case

Attribute	1	3	5
Raw Material Renewability	0-25 % of raw materials are renewable	50-75 % of raw materials are renewable	100 % of raw materials are renewable
Recycling Approach	Material has very low recycling rates in construction leading to most demolition waste being brought to landfill or being incinerated	Material when used in construction is mostly downcycled into material that can be further used in the construction industry	Material is recyclable with little to no preprocessing and can be recycled to use instead of virgin material and has very high recycling rates when used in construction
Environmental Impact of Production on Human Health	ReCiPe Endpoint impact score [EIP/FU] of material production on human health above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on human health in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on human health in 20th percentile of all materials evaluated
Environmental Impact of Production on Ecosystems	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on ecosystems in 20th percentile of all materials evaluated
Environmental Impact of Production on Resources	ReCiPe Endpoint impact score [EIP/FU] of material production on resources above 80th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on resources in between 60th and 40th percentile of all materials evaluated	ReCiPe Endpoint impact score [EIP/FU] of material production on resources in 20th percentile of all materials evaluated

Table 4.4: Ranking scales of Future Availability attributes for marine construction case

Attribute	1	3	5
Short Term Availability of Raw Materials	Raw material reserves/production ratio below 25 years	Raw material reserves/production ratio between 50-75 years	Supply large to unlimited so that data on reserves is not exactly available or reserves to production ratio over 100 years
Long Term Availability of Raw Materials	Raw material resources/production ratio below 50 years	Raw material resources/production ratio between 100-125 years	Supply large to unlimited so that data on resources is not exactly available or reserves/production ratio over 150 years
Geographic Distribution of Reserves	Herfindahl-Hirschmann-Index of raw material reserves larger than 2500	Herfindahl-Hirschmann-Index of raw material reserves from 2150-1850	Herfindahl-Hirschmann-Index of raw material reserves below 1500
Potential for Restrictive Government Regulation	Regulations limiting the supply of raw materials will be implemented in the near future or are already in place and strongly limit the availability of raw materials	Uncertain whether regulations limiting access to raw materials will be implemented, but the possibility exists	No realistic reason for governments to regulate usage of material or raw material in the foreseeable future
Development of Recycling Infrastructure	Recycling infrastructure will not develop significantly in the next 50 years leaving landfilling or incineration as the main disposal option for material	Recycling infrastructure will develop to a certain extent increasing recycling rates. However, downcycling is expected to remain the only viable option	Infrastructure will develop strongly in the next 50 years leading to high recycling rates (> 75 %) of material that can replace virgin material or recycling rate is already at this level today
Projected Growth of Competing Industries	Construction is only responsible for a small share of material's total demand and demand from competing industries is expected to exceed current supply levels in the next 50 years	Along with other industries the construction industry is a major consumer of the material. As demand increases it is possible that competition for resources between these industries increases	The construction industry is the largest driver of demand for the material and demand from competing industries will become/remain insignificant compared to supply levels in the next 50 years
Ease of Production Increase	Increase in production would require extensive investments into new facilities and the development of new production or manufacturing technologies	Increasing production would require new facilities or adaption/expansion of existing facilities with limited investments	Production could be significantly increased with existing infrastructure (mining, processing facilities etc.)

4.2.2 Weighting Factors

The *weights* of the individual categories and attributes were defined together with industry experts in order to represent the stated goal of the ranking (see Chapter 4.1) and are shown in Figure 4.1. Since the focus is on sustainable marine construction in the long-term future, immediate economic considerations were seen as less important while future availability was determined to be the most central category.

Durability (2)	
Corrosion Resistance	(3)
Resistance to Biological Degradation	(3)
Fatigue Resistance	(1)
Resistance to Stress Corrosion Cracking	(2)
UV Resistance	(1)
Moisture Resistance	(3)

Sustainability (2)	
Raw Material Renewability	(2)
Recycling Approach	(3)
Impact of Production on Human Health	(2)
Impact of Production on Ecosystems	(2)
Impact of Production on Resources	(2)

Economics & Costs (1)	
Material Costs	(3)
Ease of Manufacture	(1)
Maintenance Cost - Vulnerability	(3)
Maintenance Cost - Repairability	(3)
Reaction to Fire	(2)
Resistance to Fire	(2)
Performance Uncertainty	(1)
Projected Price Developments	(1)

Future Availability (3)	
Short-Term Raw Material Availability	(2)
Long-Term Raw Material Availability	(3)
Geographical Distribution of Reserves	(3)
Potential for Restrictive Government Regulation	(2)
Development of Recycling Infrastructure	(3)
Projected Growth of Competing Industries	(2)
Ease of Production Increase	(1)

Figure 4.1: Category and attribute weights used for marine construction case

4.3 Material Selection

Material selection was intended to include not only the most commonly used materials, but also materials that exhibit favorable properties but have so far not been applied widely in marine construction. In a first step existing textbooks on material science and engineering were analyzed to determine the generally accepted categories of materials that are used in engineering and construction (*212*, *251–254*). To bring the number of materials down to a manageable level, materials were grouped into subcategories containing materials with very similar chemical compositions (Ex. carbon steels, aluminum alloys, softwood timber etc.). Although the materials in such a subcategory may exhibit different properties depending on their exact composition, the differences will be significantly smaller than when compared to materials in other subcategories. Some materials such as reinforced concretes or fiber reinforced composites are composed of multiple component materials (i.e. matrix and reinforcement). Nevertheless, these materials were treated as a single material for the purpose of this ranking, as the properties of the combined material are inherently different than those of the individual components.

As the analysis is limited to structural materials for the use in large scale construction it was estimated that the *mechanical requirements* for the ranked materials would be a minimal stiffness (Young’s Modulus) of 10 GPa, a minimal compressive strength of 25 MPa and a minimal tensile strength of 40 MPa. All materials with lower mechanical properties were removed from the ranking. Furthermore, materials which are almost exclusively used in mechanical engineering and not construction (such as technical ceramics) as well as recently developed materials for which little data exists were also removed. Finally, the list of candidate materials was discussed with several industry experts to ensure no relevant materials were missing. The material categories and subcategories included in the final ranking are shown in Figure 4.2. For each material subcategory one specific material, most commonly used for marine construction, was chosen to represent the category.

The individual materials, subcategories and categories, will be presented in detail in the following subsections.

Category	Subcategory	
Metals	• Carbon Steel • Stainless Steel • Aluminum Alloy • Titanium Alloy • Nickel Alloy	
Concrete	**Cement Type** • Blended • Alkali Activated (Geopolymer) • Calcium Sulfoaluminate	**Reinforcement Type** • Steel • Stainless Steel • GFRP • CFRP
Composites	**Matrix Type** • Thermoset – Phenolics – Polyester – Epoxy – Vinylester • Thermoplastic – Commodity Plastic – Engineering Plastic	**Fiber Type** • Glass • Carbon • Basalt • Natural C4
Timber	• Softwood • Non-Tropical Hardwood • Tropical Hardwood	

Figure 4.2: Materials included in marine construction case

4.3.1 Metals

4.3.1.1 General Overview

Metals have played an important role in marine construction in the past. Due to their high toughness, stiffness and strength they were used extensively for the production of not only large-scale structural components such as ship hulls, support columns for off-shore platforms and pressure vessels, but also for pipelines, tethering attachments and reinforcement of concrete structures (*251*, *255*, *256*). Despite the emergence of newer material classes such as ceramics or fiber reinforced polymer composites in the past decades, metals will remain exceedingly important materials for marine infrastructure in the future.

However, the production of metals is associated with large environmental impacts and the raw materials for various metal alloys are non-renewable and can be highly geographically concentrated (*226*, *244*, *245*, *257*). Considering the impact a lack of availability of central alloys required in marine construction could have on the development of the industry and the time for new alternative material compositions to be developed, tested and introduced into the market, it is essential to identify such supply risks early on and to begin developing mitigation strategies long before supply shortages occur.

4.3.1.2 Selection of Individual Materials

For the selection of the individual metal subcategories existing categorizations of metals used in marine construction were analyzed (*179, 212, 251, 253*). This led to a first selection of broad metal categories, which each include the pure metals as well as the plethora of individual alloys of the specific metal type. The categories commonly used in literature are carbon steels (CS), stainless steels (SS), aluminum alloys (AA), titanium alloys (TiA), nickel-copper alloys (Ni-Cu), magnesium alloys and zinc alloys. After discussion with industry experts it was decided to exclude magnesium and zinc alloys from the ranking. Magnesium and zinc are extremely low on the galvanic series and corrode rapidly in seawater. Consequently, they cannot be used as structural materials in these environments. For each of the remaining metal categories one specific alloy was chosen to represent the entire category. This choice was based on discussions with experts and literature review to identify the alloy that commonly provides a good performance in the marine environment. For the CS, S355J2 (1.0553) was chosen as the representative material as it is a versatile structural steel specified for marine use by various codes such as BS EN 10225:2009. The most commonly used SS are austenitic steels since they are also the cheapest. However, these steels may still corrode in aggressive environments as can be found offshore in the splash zone. Therefore, to reflect more precisely the material used for marine construction, duplex stainless steel grade 1.4462 (X2CrNiMoN22-5-3) was selected to represent the category as it combines the advantages of both austenitic and ferritic stainless steel and is the most suitable material for the use in corrosive environments (*258*). For the AA, the 5xxx series containing magnesium as the main alloying element are mainly used for structural applications due to their increased corrosion resistance (*259*). Alloy 5083 (AlMg4.5Mn) was chosen as the representative material for this group. The most used TiA for marine environments is grade 5 titanium (3.7165 - Ti6Al-4V). This alloy accounts for around 50% of global titanium alloy production (*260*). Finally, for Ni-Cu, Monel K500 (2.4375 - NiCu30Al) is used as the representative material.

4.3.2 Fiber Reinforced Polymer Composites

4.3.2.1 General Overview

Over the past decades fiber reinforced polymer composites (FRPC) have been used more and more frequently in a wide range of applications in vehicles, aircraft, ships and also civil infrastructure. More recently, FRPCs have also been used as external (fabric or plates) and internal (rebar) reinforcement for concrete structures and also as fully structural members (*261–263*).

In marine environments FRPCs have, in many cases, replaced more traditional materials such as aluminum or steel due to their high specific strength, excellent corrosion resistance and consequently lower life cycle costs (*264*, *265*). Due to the artificial combination of two distinct materials (fiber and polymer resin) a plethora of different components with highly diverse and tailored mechanical properties can be constructed making the selection of appropriate material combinations a challenging task.

While the durability of these materials under the harsh conditions present in the marine environment has been investigated extensively (*266–271*), the comparability of this data is limited due to the wide amount of experimental parameters affecting the final results (*272*). Furthermore, existing performance evaluations focus solely on mechanical and durability aspects, thus failing to address the question whether the production, use and disposal of such FRPCs is actually sustainable in the long-term.

4.3.2.2 Selection of Individual Materials

In this thesis different materials were considered for the matrices and fibers of the composites. The selection was completed with industry experts to include commonly used materials, as well as less established ones, that may become more widely used in the future. The most commonly employed FRPCs are reinforced either with carbon fibers (CF) or glass fibers (GF). In light of the growing importance of sustainability considerations in society, composites containing natural, plant-based fibers (NF) have been gaining increasing interest as low cost, environmentally friendlier alternatives (*273*). Another fiber type that is seeing increasing usage are basalt fibers (BF) made from basaltic rock, which is a widely available resource in certain regions. These fibers require less preprocessing than GF and provide similar mechanical strength, thus presenting another viable alternative (*274*, *275*). Thus, GF, CF, NF and BF were included in the ranking.

For the matrices three different thermoset resins (Epoxy (E), Polyester (PE), Vinylester (VE)) as well as a general thermoplastic (TP) polymer was included.

For the NFs, jute was chosen as the representative material, while polycarbonate was chosen to represent the TP resins.

4.3.3 Cement and Concrete

4.3.3.1 General Overview

Cement and thus consequently concrete is the single most produced material in the world and a central component of today's society. Concrete is durable, cost-effective and can be handled by professionals and laymen almost anywhere in the world. Additionally, the materials required for cement and concrete production are globally widespread and almost always locally available. The biggest issue associated with the enormous scale of global concrete use, are the CO_2 emissions associated with the production of cement, through the burning of limestone. The cement industry is responsible for around 8% of global CO_2 emissions and global cement demand is predicted to continue rising in the coming decades. Consequently, the industry has laid out a roadmap which includes multiple approaches to reducing these emissions and further increasing the efficiency of global cement and concrete production and use (*233*, *276*). These strategies include the use of alternative fuels for the use in cement kilns, substitution of Ordinary Portland Cement (OPC) clinker, carbon capture and storage (CCS) and the use of alternative clinkers. Although CCS is still seen as a part of the total solution, the material solutions (clinker substitution with supplementary cementitious materials (SCM) or alternative clinkers) are seen as more cost-effective and feasible strategies.

Next to the blended cements (BC), where OPC is substituted with different SCMs, the alternative clinkers which have been most extensively developed are belitic clinkers containing ye'elemite phases (referred to in this work as calcium sulfoaluminate (CSA) cement) and alkali activated cements (AAC) (*277–279*). CSA cements were developed as low energy, low carbon alternatives to OPC. They produce significantly less CO_2 during production than OPC; directly due to a lower limestone content required per unit clinker, and indirectly due to reduced energy requirements for grinding and kiln operation. However, this advantage is currently still outweighed by the higher production costs, caused by the larger amount of aluminum rich raw materials used to replace limestone (*280*). While BCs and CSA cements can be produced in conventional cement kilns and have the same mechanism and products of hydration (only different raw material and thus phase distributions), AAC cements have a fundamentally different mode of hardening. For the production of AAC a solid aluminosilicate precursor and an alkali activator are required. The high alkalinity of the activator initiates the reaction of the solid precursor to form a hardened binder. The activator is usually sodium hydroxide and sodium silicate in solution, while the solid precursor can range from fly ash (FA) and granulated blast furnace slag (GBFS) to calcined clays and other natural pozzolans (*281*). As these materials are either waste materials from other industries (FA, GBFS) or do not release any CO_2 during binder production, they are seen as a potential substitute for BCs (*282*).

Another option for reducing global emissions is to reduce the amount of concrete used in the built environment. In many cases too much concrete is used to produce a given structure. This can be caused inadvertently through improper planning, but also deliberately for safety reasons. The prediction of concrete lifetime is still difficult and therefore higher safety factors are used than actually may be necessary. The main durability concern of concrete structures is the corrosion of the steel rebar (*180*). To solve this problem again multiple approaches ranging from increasing cover depth to the addition of corrosion inhibiting supplementary materials are being employed. An interesting approach is the use of alternative rebar materials, which are inherently corrosion resistant such as stainless steel or fiber reinforced polymer rebar (*263, 283*). These alternative cements and rebar types have been shown to offer either improved durability, lower environmental impact, or both (*279, 280, 282, 284–287*).

4.3.3.2 Selection of Individual Materials

For this evaluation concretes produced from three different cement types (blended, alkali activated, and belite ye'elemite) were included. For modern constructions, OPC is almost always mixed with other materials exhibiting cementitious activity such as clays, FA or GBFS to reduce clinker content. Consequently, BC is used as the standard cement in this evaluation. According to the British construction standard BS 6439-1-4:2013 a very durable concrete for the marine environment is so-called CEM IIIA which contains 35-64% clinker (OPC) and 36 – 65% GBFS (*178*). This concrete was chosen to represent the material category of BC concretes. For the AAC evaluations in this study, FA was chosen as the solid precursor, while sodium silicate solution and NaOH were chosen as the activators (*288*). For the CSA cement, which as mentioned has a higher aluminate mineral and lower limestone content than OPC, a commercially produced CSA cement was chosen for the calculations (*289*).

As pure concrete exhibits a high compressive strength but is relatively weak in tension, most large-scale structures are made from concrete reinforced with rebar (most commonly steel). Therefore, only reinforced concrete was evaluated in this study. The analyzed rebar materials include CS, SS, GFRP and CFRP. As for the cements and concretes one specific material was chosen to represent the corresponding rebar class in this study. For CS, steel grade B500A which corresponds to DIN 1.0438 was chosen as it is a the most commonly used reinforcing steel specified in various building codes such as BS 4449:2005 (*290*). For concrete structures in marine environments class 2 (austenitic) or 3 (duplex) SS rebar is recommended (*283*). Due to the specific applicability to aggressive marine environments, grade 1.4462 duplex SS was selected. The two most commonly used non-metallic rebar materials are GFRP and CFRP (*291*). For both materials different polymers can be used. Epoxy, a cheap and commonly used resin, was chosen in this thesis.

4.3.4 Timber

4.3.4.1 General Overview

As the only fully renewable material available in large sizes and exhibiting sufficient mechanical strength, timber, which has been used extensively throughout history, is regaining interest as a material for the construction of large-scale infrastructure and multistory buildings (*292, 293*). Although the renewability of timber is a major advantage compared to for instance concrete or steel, the time required for trees to grow to sizes useable in construction can reach multiple decades. This leads to the necessity for a long-term planning approach concerning timber production, as uncontrolled logging of timber can significantly damage local ecosystems decreasing their carbon sequestration potential and thus contribute to increasing atmospheric carbon levels (*44*). Another advantage, the biodegradability of timber also means that timber components are susceptible to many biological and chemical damage mechanisms which do not affect other materials used in construction. This susceptibility leads to a decreased durability of timber components in certain environments if no protection measures such as coatings or impregnations are applied (*294, 295*). Such tradeoffs need to be taken into account when deciding to use timber as the main structural material in large-scale construction as they affect the overall economics and sustainability of the structure.

4.3.4.2 Selection of Individual Materials

The timbers were divided into three broad categories which are commonly used to classify timbers used in construction, softwoods, non-tropical hardwoods and tropical hardwoods. While many different species exist for each category, the performance and availability differences within a category will be significantly smaller than between the categories. Therefore, European Larch (*Larix decidua*), Black Locust (*Robinia pseudoacacia*) and Ekki (*Lophora Alata*) were chosen to represent the categories of softwoods, non-tropical hardwoods and tropical hardwoods respectively. Engineered timber products were not included in the ranking as the goal is to compare the performance of pure (untreated) timber to the most commonly used non-renewable construction materials.

4.4 Data Collection

Data on the performance of the individual materials for each attribute was gathered through discussions with experts, as well as literature, technical reports and material databases. For each material at least three different experts were asked to complete the ranking and state their reasoning behind each attribute score to minimize subjectivity. The individual arguments were cross-checked with data from current literature. If similar scores were given to a specific attribute the score assigned by the majority was selected. If the given scores varied by more than 1 point, a more in-depth literature research was conducted to inform the decision on which value was appropriate. Overall a total of 23 experts from academia and industry completed the ranking for at least one material category.

5 Ranking Results & Discussion

In this chapter all the results of the application of the framework to the case of marine construction are presented. The first four subsections each cover a separate material category and describe the ranking results for each individual material. In each section the goal of the individual ranking is first stated. This is followed by a description of the composition and mechanical properties of the individual materials, as well as the definition of the FU used. Then, the results of the ranking are presented by explaining the reason behind each individual attribute score in detail. It is then discussed which materials present themselves as promising and sustainable options in the long-term future, which materials should be avoided, and how certain materials could be greatly improved through specific research foci or policy measures.

The first subchapter discusses the use of different metal-alloys for marine construction. Next to the comparison of the different alloys, focus is put on using the results of the ranking to identify the most promising options for improving the individual materials' long-term performance. For each metal, multiple critical weaknesses are identified, and the effect of different improvement approaches on specific attribute scores of the material are discussed. The main topics discussed are corrosion resistant coatings, more sustainable mining practices and the effects of various recycling technologies. As all the evaluated metals have been extensively used for large scale construction in the past, this subchapter demonstrates the application of the framework to compare established materials with lots of existing performance data, assess their overall criticality, and evaluate how to further improve different attributes in the long term.

The second subchapter covers the category of fiber reinforced polymer composites. Two of the four evaluated fiber types, BF and NF, are relatively new materials and have so far not been used extensively in construction. Therefore, especially for the BF composites, the ranking scores are based on estimates made by experts. This demonstrates how the framework can be applied to compare existing materials with potential new alternatives on a high level, even if not much experimental data is available.

Chapter 5.3 presents the results of the evaluation of the different concretes. Here, the results are used to evaluate the effect a number of material development and policy measures have on the individual scores of the different concretes, which enables a first high-level prioritization of these approaches.

The final material category, timber, is discussed in Chapter 5.4. The results show where the strengths and weaknesses of these renewable materials lie and again allow for the identification of research projects which address the main weak points of the timbers, thus potentially leading to more widespread use of renewable and more sustainable construction materials.

Following these discussions focusing on one individual material type, the true potential of the framework is demonstrated in Chapter 5.5. Namely, to compare materials that are completely different from a chemical and physical perspective along a single set of criteria. Thus, the identification of research areas and policy measures that target the improvement of multiple material types is possible, presenting a broader approach to more sustainable construction. The results are focused on presenting the general strengths and weaknesses of each material category (i.e. metals, FRPCs, concretes, timbers), while the discussion is centered around the material development projects that may prove promising for the 15 highest ranked materials, as well as those policy measures that have a positive effect across multiple categories. As the individual materials and potential improvement approaches were already discussed in the previous sections, this chapter summarizes information already presented.

5.1 Metals

5.1.1 Goal of Ranking

The goal of the ranking presented in this section is to identify the types of metals that have the highest potential to be used as structural components for sustainable marine construction in the long-term future. The individual metals are evaluated without considering any protection methods (ex. coatings).

5.1.2 Definition of Functional Unit

The FU chosen to compare the different metals according to their performance as structural components was related to the materials' tensile strengths. Thus, it was calculated for each metal how much material would be required for the production of a 1 m long beam with a square cross section that is able to withstand a tensile load of 5000 kN. Consequently, the tensile strength of each metal determines the area of the cross section and thus also the amount of material required (i.e. the FU).

5.1.3 Composition and Mechanical Properties

In order to accurately calculate EI of production as well as the Future Availability attributes, the exact composition and mechanical strength of each alloy specified in Chapter 4.3.1 was researched. An overview is given in Table 5.1 as well as Appendix A.6.

Table 5.1: Elemental composition of analyzed alloys (based on data from 296)

Metal Class	Specific Alloy	Material Composition in weight %	Tensile Strength [MPa]
Carbon Steels	S355J2 / 1.0553	Fe (balance), Mn (1.6), Cu (Max 0.55)	550
Stainless Steels	X2CrNiMoN22-5-3 / 1.4462	Fe (balance), Cr (22), Ni (5), Mo (3), Mn (2)	795
Aluminum Alloys	AlMg4.5Mn / 5083	Al (balance), Mg (4.4), Mn (0.7), Cr (0.15)	248.5
Titanium Alloys	Ti6Al4V / 3.7165	Ti (balance), Al (6), V (4), Fe (Max 0.4)	932.5
Nickel Alloys	NiCu30Al / 2.4375	Ni (balance), Cu (30), Al (2.7), Ti (0.6), Fe & Mn (Max 2)	765

5.1.4 Metal Ranking Results

The individual attribute and category scores are shown in Table 5.2, providing an overview of each metal's strengths (values 4-5) and weaknesses (values 1-2).

The highest durability scores are achieved by the corrosion resistant TiA and Ni-Cu followed by SS, AA and finally CS. The economics scores show almost the exact opposite ranking (CS>AA>SS>TiA>Ni-Cu), as the less alloyed metals are cheaper to produce and somewhat easier to manufacture. The same ranking resulted for the sustainability category. While all metals are non-renewable and highly recyclable, the mining and processing of more specialized alloying elements leads to significantly higher EI of production (per FU) for SS, Ni-Cu and to a lesser extent TiA, despite their higher tensile strengths (Table 5.3). Concerning future availability, the most critical materials are nickel, chromium and molybdenite leading to low scores for SS and Ni-Cu. In the longer term these alloys (as well as TiA) will furthermore see strongly increasing demand from other industries beside construction, exacerbating potential supply concerns. For AA competition may also be an issue, but this is less certain. No competition or availability shortage is expected for CS.

Combining the individual scores of each metal using the weighting factors presented in Figure 4.1 leads to the total scores shown at the bottom of Table 5.2. Despite having a lower durability than all the other metals, the low cost and EI of production (on a relative scale, the impact is still rather high, when compared with other materials such as timber or concrete) as well as the high future availability results in CS achieving the highest overall score. The second highest ranked material is TiA, mainly due to its high durability. This is followed by AA, Ni-Cu and finally SS. The performance of the individual metals will be discussed in detail in the following subsections.

Table 5.2: Ranking results including attribute, category and total scores for the analyzed metals

	Metal	Carbon Steel	Stainless Steel	Aluminum Alloy	Titanium Alloy	Nickel-Copper Alloy
	Alloy	S355J2	X2CrNiMoN22-5-3	AlMg4.5Mn	Ti 6Al-4V	NiCu30Al
		1.0553	1.4462	5083	3.7165	2.4375
Durability	Corrosion Resistance	1	4	4	5	5
	Resistance to Biological Degradation	3	3	3	5	5
	Fatigue Resistance	3	3	2	3	2
	Resistance to Stress Corrosion Cracking	2	4	3	5	5
	UV Resistance	5	5	5	5	5
	Moisture Resistance	5	5	5	5	5
	Category Score	3.00	3.93	3.64	4.71	4.51
Economics & Costs	Material Costs	5	3	4	2	1
	Ease of Manufacture	4	3	4	3	4
	Maintenance Cost - Vulnerability	4	4	3	4	4
	Maintenance Cost - Repairability	5	4	4	2	5
	Reaction to Fire	5	5	5	5	5
	Resistance to Fire	2	2	2	5	2
	Performance Uncertainty	5	4	4	5	4
	Projected Price Developments	3	2	2	2	1
	Category Score	4.25	3.50	3.56	3.38	3.31
Sustainability	Raw Material Renewability	1	1	1	1	1
	Recycling Approach	5	5	5	5	5
	Impact of Production on Human Health	5	2	4	3	1
	Impact of Production on Ecosystems	5	4	3	1	2
	Impact of Production on Resources	5	1	4	3	2
	Category Score	4.27	2.82	3.55	2.82	2.45
Future Availability	Short-Term Raw Material Availability	2	1	1	1	2
	Long-Term Raw Material Availability	5	2	5	5	2
	Geographical Distribution of Reserves	4	1	1	1	4
	Potential for Restrictive Government Regulation	5	2	4	5	2
	Development of Recycling Infrastructure	5	5	5	5	5
	Projected Growth of Competing Industries	5	1	3	1	1
	Ease of Production Increase	5	3	3	2	2
	Category Score	4.44	2.19	3.25	3.06	2.81
	Total Score	4.39	3.44	3.92	4.04	3.80
	Rank	1	5	3	2	4

5.1.4.1 Durability

With the exception of CS, all analyzed metals have a very high Durability rating. All metals are immune to damage from UV radiation and are not affected by moisture (excluding corrosive effects), thus achieving the highest score in these categories. TiA and Ni-Cu are furthermore considered as inherently corrosion resistant (Ni-Cu is often used as protective cladding for marine steel structures) and are also not susceptible to biological degradation and stress corrosion cracking (SCC) (*253*, *297*). In fact, the only attribute where these metals do not achieve the maximum score is fatigue resistance.

All metals are susceptible to fatigue damage. Nevertheless, their fatigue behavior is well understood and can be predicted rather precisely. Therefore, for metals with a fatigue limit (CS, SS, TiA) structures with an infinite fatigue life can theoretically be designed, if the loads a component will be exposed to during its service life are known (score 3). This is not possible for metals without a fatigue limit (AA, Ni-Cu), which is why these metals have a lower fatigue score (i.e. 2).

The next best metals concerning Durability are SS and AA. Duplex SS perform very well in the marine environment. However, they can still suffer from pitting corrosion. It has been shown that the depth of these pits increases rapidly after initiation but remains constant after a period of several years (*298*). Therefore, for thicker stainless steel components this pitting corrosion can be seen as mostly superficial affecting the visual aspects and not the mechanical ones. A lifetime of 50-100 years should be achievable (*258*). Nevertheless, since the initiation of corrosion can under certain circumstance lead to failure of a component a score of 4 was assigned. The same score was assigned for AA, which are corrosion resistant due to the formation of a passive oxide layer on their surface. If this layer is damaged localized pitting corrosion can also occur.

For both SS and AA biological attack presents an issue in the form of microbially induced corrosion (MIC). Certain microorganisms can become attached to SS and AA components and give rise to slimy biofilms on the surface. These films can accelerate the initiation of pitting corrosion which can lead to sudden failure of a component (score 3) (*234*).

Concerning SCC Duplex SS perform better than AA. Both are generally not susceptible to SCC. For AA however certain tempers as well as defects during manufacture can strongly increase SCC susceptibility (*299*). Due to this possible susceptibility a score of 3 was assigned. Duplex SS do not exhibit this behavior but are still not completely immune to SCC (score 4).

CS as the lowest ranking metals readily corrode in seawater (score 1), are also susceptible to biological attack in the form of MIC (score 3) and in the past have commonly failed due to SCC mechanisms when used in marine structures without the appropriate maintenance or protection (score of 2) (*300*).

5.1.4.2 Economics and Costs

Concerning Economics and Costs all metals perform well. The main weaknesses are fire resistance and increasing prices in the future. The ranking of the total Economic scores is the same as that of material costs per FU. CS are the cheapest of the analyzed materials followed by AA which cost about 100% more per FU. The more complex Duplex SS, TiA and Ni-Cu are significantly more expensive due in part to the higher content of specialized alloying elements such as chromium, molybdenum or vanadium, and achieved scores of 3, 2 and 1 respectively (The costs per FU for each metal are shown in Table 5.3).

Concerning Ease of Manufacture, all metals have similar properties. Larger components such as sheets, rods and bars are produced in a factory for all analyzed metals. Theoretically, any shape or size can be produced. For CS and Ni-Cu, components can easily be resized and joined on-site with simple welding equipment. To a certain extent these components can also be reshaped. Nevertheless, the main design of the component produced in the factory largely determines the final shape that is used on-site (score 4). AA achieved the same score even though on-site welding of Al components is more difficult than for CS or Ni-Cu, as this disadvantage is compensated by the lower stiffness of AA making it easier to reshape components on-site. SS and TiA were given a lower score, as welding and reshaping on-site is not easily completed (score 3). For SS more caution needs to be given when handling components to make sure the surface isn’t damaged or contaminated which would reduce corrosion resistance (*258*). Thus, the environment needs to be carefully controlled during casting and also welding, jointing and cutting, necessitating more specialized equipment and better trained personnel. Especially the welding of duplex SS is a big challenge even for trained personnel, making factory conditions much more suitable for manufacture than on-site ones. For TiA the primary and secondary fabrication processes are up to 18 times more costly than when using CS. This is due to the hardness and reactivity of titanium which wears down tools very quickly and requires a slow fabrication process (*301*). Thus, it requires expensive specialized equipment for manufacture. Furthermore, it is very difficult to shape TiA components on-site making factory production of the complete final components a necessity.

The Ease of Manufacture of the different metals has a direct consequence on their Repairability. As CS and Ni-Cu can be rather easily be welded the repair of damaged components is possible on-site even to the extent of restoring original mechanical properties (score 5). The same can be done with AA and SS components although more sophisticated equipment and specially trained personnel is required (score 4). For TiA the hardness of the material makes it very difficult to cut out a damaged area before welding on-site. Thus, removal of the entire component and repair in a factory are a more feasible approach (score 2).

Fire resistance is an issue for all unprotected metals except TiA which have an excellent heat resistance (score of 5). The high thermal conductivity of metals leads to a rapid temperature increase throughout the entire component in the case of a fire. If unprotected, they lose their mechanical strength at lower temperatures than those present in an average fire and thus fail under standard service loads. Nevertheless, for any given load it is possible to calculate the time it will take for a specific component to fail in a fire, making the failing behavior predictable (score 2).

All analyzed metals have been used for decades in marine construction and thus have a low performance uncertainty. The difference in individual scores is due to the fact that some metals have been used extensively for larger structural components (CS, TiA score 5), while others are more commonly used for non-structural uses such as pipes, valves, cladding or handrails (SS, AA, Ni-Cu, score 4).

Finally, in the long term, for all metals except CS a significant price increase is expected in the foreseeable future. The main drivers for these increases differ from metal to metal. For instance, global aluminum prices are expected to increase by over 30 % by 2030 compared with 2016 (*302*). This will have a large effect on the future prices of AA and to a certain extent also for TiA as aluminum is used as an alloying element. The prices for titanium minerals (ilmenite & rutile) are also predicted to increase in the range of 5-15% from 2017-2020. It is expected that suppliers will aim to keep price increases steady but moderate (*303*). A critical point for TiA is vanadium. In the near term a price spike is expected for vanadium as demand exceeded supply in 2017. However, as new capacity comes online these prices are expected to stabilize (*304, 305*). Overall vanadium is only added as an alloying element in small amounts (4% of mass) but will nevertheless influence the final price of grade 5 titanium. For duplex SS, rising prices for raw materials (excl. iron ore) are seen as one of the main restraints for future growth of the industry. Increased use of scrap (which will occur if prices are high) could limit these increases (*306*). The highest increase in price is expected for nickel (an alloying element in SS and the main component of Ni-Cu). Due to decreasing production levels and increasing demand from green technologies such as batteries, turbines or electric motors an increase of up to 100% is expected from 2016 to 2030. Furthermore, copper prices are also expected to increase by around 40% in the same timeframe (*302*). Thus the lowest value was assigned for Ni-Cu.

5.1.4.3 Sustainability and Environmental Impact

Concerning Sustainability, the only positive aspects of the analyzed metals is their high recyclability. The recycling rates are above 60% for all metals, which corresponds to the highest score (*307–309*). However, none of the raw materials required for production of the individual alloys are from renewable sources, translating into the lowest score for Renewability.

The individual EIs were calculated for the production of 1 FU of the specific metal from 100% virgin materials using data from the Ecoinvent 3.3 database (The individual scores are shown in Table 5.3. Information on the individual calculations can be found in Appendix B). CS have the lowest EI for all three categories analyzed (Human Health, Ecosystems, Resources) and thus the highest score for these attributes. This is once again due to the low content of alloying elements. For instance, SS and Ni-Cu with the overall highest impact require nickel and for SS also molybdenum, both of which are largely mined as sulfide minerals. The hydrometallurgical processing of these minerals leads to large impact scores from emissions and leaching of the sulfide tailings. Overall, these direct impacts are larger than the indirect impacts from energy production which are significant for the energy intensive production of AA and TiA (*257*, *310*). It must be kept in mind that the EI rankings are based on the relative values of the analyzed material and thus cannot be directly translated into "environmental friendliness" of production.

Table 5.3: Mass, price and EI of production per FU of analyzed metals (based on data from 296 and EI calculations shown in Appendix B)

Metal Type	kg/FU	Price [$/FU]	Environmental Impact [Pt/FU]			
			Human Health	Eco-systems	Resources	Total
Carbon Steels	70	48.4	5.5	1.8	11.1	18.3
Stainless Steels	49.1	309	174.9	7.9	126.2	309
Aluminum Alloys	53.4	108.7	24.5	10.3	21.4	56.1
Titanium Alloys	23.8	491.7	37.9	15.8	22.3	76.1
Nickel Alloys	55.4	783.8	197.8	15.1	111.3	324.2

5.1.4.4 Future Availability

The Future Availability scores for all materials are determined by the raw materials required for their production. Table 5.1 describes the elemental composition of the individual alloys, while Table 5.4 shows the raw materials from which each element is produced as well as their availability and concentration values.

The overall Future Availability score for CS stands out from those of the other metals. The raw material resources of all raw materials required for the production of carbon steel (Fe, C, Cu) are large and geographically well distributed. Furthermore, the construction industry is the main user of steel and the only competition could potentially come from the automotive industry, which is predicted to grow strongly in the coming decades due to increased demand from developing nations. However, the automotive industry is moving strongly towards more lightweight materials such as aluminum or composites. Therefore, the demand for steel from the automotive industry will very likely be significantly lower than the demand from the construction industry. Concerning manganese, the main alloying element in low carbon steels, the steel industry is the major consumer responsible for around 90% of global demand and therefore this should not lead to a shortage in supply for the construction industry (score 5). Finally, demand growth for steel is slowing down after a period of very strong growth driven largely by China. Many steel producers already have or may soon have significant overcapacities. Some facilities have even been shut down to improve the carbon footprint of producing companies. Therefore, a certain increase in production volumes should be possible with existing facilities. The past surge in demand for steel by China demonstrated that significant production capacity can be added in a very short period of time (score 5) (*311–313*).

Table 5.4: Availability and geographical concentration of raw materials (Calculated with data from 246)

Element	Raw Material	Short-Term Availability (Reserves / Production Ratio)	Long-Term Availability (Resource / Production Ratio)	Geographical Distribution HH-Index of Reserve Concentration
Al	Bauxite	107	286	1538
Cr	Chromite	17	Large	3890
Cu	Copper Ore	37	>300	1678
Fe, C	Iron Ore	60	169.0	1589
Mg	Various	Virtually Unlimited	Virtually Unlimited	Globally Widespread
Mn	Manganese Ore	43	Large	1840
Mo	Molybdenite	66	85	3662
Ni	Laterites (60%) Sulfite deposits (40 %)	35	58	1164
Ti	Ilmenite (89 %), Rutile (11 %)	126	>300	1514
V	Various (often recovered as a byproduct)	4	>300	3246

In comparison the score for SS, the lowest ranking metal type concerning future availability, is greatly affected by the use of nickel, chromium and molybdenum as alloying elements. All three elements either have a limited short- or long-term availability (score 1 and 2 respectively), while chromium and molybdenum reserves are also highly concentrated (score 1). Furthermore, government regulations which have an impact on the production of SS are already in effect. For instance, the government of Indonesia restricted the export of unprocessed nickel ore in order to ensure that the value increasing refining processes are completed in the country in 2014. Furthermore, in the Philippines the government issued an order in 2016 to audit all existing mines in the country to check for environmental compliance and to clamp down on non-sustainable mining practices, reducing output and even shutting down critical operations. These two countries together account for 31% of global nickel production and thus these developments have limited the supply of this crucial raw material on the global market and created substantial uncertainty (*314*, *315*). Further export restrictions exist for other essential raw materials of SS such as chromium and even SS scrap. These export restrictions have a high potential to limit (but not completely restrict) supply of raw materials especially for the European Union, which is responsible for around 20% of global SS production and a much larger percentage of global duplex grade production (score 2)(*316*). To add to these issues, the construction industry is only responsible for around 12% of total stainless steel demand (this includes all grades) and demand from competing industries is expected to increase strongly (score 1). The major concern comes from a strong expected growth of the renewable energy and electro mobility sectors that would lead to large demand increases for nickel and also molybdenum. Kleijn et al. estimated the increased metal supply that would be required under different energy scenarios and came to the conclusion that nickel output would have to increase by 50-250% and molybdenum output by 30-100% to meet the rising demand from the energy sector alone (*317*). Even if supply security can be achieved, increasing the production of duplex SS will only be possible with large capital investments (score 3). As most facilities which currently produce duplex SS do not have large overcapacities, new facilities will need to be constructed. If these facilities are to be built in countries that are currently not yet producing duplex SS, careful technology transfer will be required, as the process for producing these high quality materials is significantly more complicated than those used to produce austenitic SS or CS.

For AA the main bottleneck concerning availability are globally highly concentrated chromium reserves (score 1) combined with existing export restrictions mentioned before (as it is only a minor alloying element in the 5xxx series a value of 4 was assigned to Potential for Government

Regulation). For the production of the AA themselves there is no real competition for raw materials as 95% of globally produced bauxite is used for metallurgical processes (*318*). However, next to construction, transport is a major end-use sector for the globally produced AA. Both sectors account for around 25% of total demand. Increase in demand from the construction of lighter weight vehicles is expected to outweigh the increase in demand from the construction sector. Currently global AA production is more or less at full capacity and further investments in new mines and production facilities are ongoing. If production increase can keep up with demand growth competition for supply should be limited (due to the uncertainty a value of 3 was assigned) (*310, 319*). Concerning Ease of Production Increase, the mentioned high level of capacity at which global aluminum production is currently running means that new mines and processing facilities would need to be built requiring large, long term investments, in order to increase global production levels (score 3).

The Future Availability of TiA suffers mainly from the high concentration of vanadium resources (score 1) as well as Demand from Competing Industries (score 1) and to a lesser extent the high investments required to increase global production levels (score 2). The main competing industry for the production of TiA is the use of titanium in pigments. 91% of mineral supply is consumed for production of TiO_2 pigments, while only around 6% are used for the production of metallic products. As the construction industry is also only a minor user of TiA, the number and size of competing industries is significant. The largest end-use sectors for TiA are aerospace, chemical processing and power generation. Demand from the aerospace industry is expected to increase significantly due to increasing production of commercial aircraft and also increasing titanium content of new aircraft. However, future titanium prices are still expected to be determined largely by the level of demand from pigment producers as the largest users of this element (*320–322*). Another issue is the use of high purity vanadium as a major alloying element in Ti-6Al-4V. Only around 4% of global vanadium production is used in titanium alloy production. The major user is the steel industry responsible for 93 % of vanadium consumption. The demand for these steels is expected to grow due to increasing construction activities specifically in China (*304*). Furthermore, growth in the green technology sector is expected to drive demand for vanadium redox batteries (specifically renewable energy and electric vehicles). By 2020 it is expected that the production of such batteries could consume about 30% of global vanadium production (*305*). Concerning Ease of Production Increase, the global titanium sponge production is currently running at around 70% capacity. Due to an oversupply in the last years as well as environmental concerns some plants were closed down or decreased production rates (*321*). Consequently, to a certain extent it would be possible to increase titanium production by reactivating plants that were shut down and running existing ones at full capacity. However, for an increase to significantly higher production levels large investments will be required as titanium production is a very expensive process were return on capital is measured in decades and not years (*323*). Furthermore, new primary mines will most likely also be required, not only for titanium, but also for vanadium which requires further investments along the entire value chain. Currently, the global high purity vanadium production required for the use in titanium alloys is running at full capacity and demand is expected to exceed supply already in 2017 (*304*).

Ni-Cu, as the second lowest ranked metals concerning Future Availability, suffer from the same issues as the SS due to the use of nickel as the main material component (low short- and long-term availability, government regulation restricting supply and high competition from other industries). A significant advantage Ni-Cu have over SS is that they don't require chromium or molybdenum as an alloying element and thus have a relatively well distributed resource base (score 4). Concerning the Competition from Competing Industries (score 1) the main use of nickel is for SS production (67%) and the main use of Ni-Cu is for the aerospace industry. Future demand is expected to increase substantially due to growing demand from energy generation, transport and food processing. As nickel producers are currently decreasing production capacity in reaction to a strong oversupply in the past years, increasing production would to a certain extent be possible by reopening closed facilities and increasing capacity of running ones. However, a ramp-up of the mostly old and deep mines would require a long time and significant investments. Furthermore, it is expected that existing capacity even with reopening of mines will need to be significantly expanded to meet future demand. As no new high-grade deposits have been discovered in a long time lower grade deposits will need to be developed, mostly in more remote regions, requiring significant investments and having higher environmental concerns (*317*, *324*).

5.1.5 Improving Performance of Metal Alloys

By analyzing the weaknesses of each material discussed in the previous sections in combination with its overall future availability, it is possible to roughly determine the research areas and approaches that have the highest probability of providing long-term benefits to the industry.

For this, the low ranked attributes (scores 1-2 in Table 5.2) which have a high weight are analyzed and, where possible, existing approaches are discussed.

For carbon steels the main weak points are Corrosion Resistance (weight 3), to a certain extent Fire Resistance (weight 2) and the high EI of Production (weight 2). For all other metals the high EI of production also presents a reason for concern. However, the main weak points lie in a low long-term availability (weight 3, for SS & Ni-Cu) or high concentration (weight 3, for SS, AA and TiA) of specific alloying elements, as well as strong competition from other growing industries (weight 2, for SS, TiA and Ni-Cu). Further, a factor reducing the overall attractiveness of TiA and Ni-Cu is price (weight 3).

Concerning CS, multiple approaches are already broadly employed to increase their corrosion resistance such as sacrificial anodes, or various kinds of organic and inorganic coatings. Further research in this area is well warranted, as carbon steel presents the best option from the sustainability and availability perspectives for all the metals and an increase in Corrosion Resistance would significantly increase the Durability and overall score of this material. However, it is essential to evaluate the Economics, Sustainability and Future Availability of the desired protection method to ensure that the addition of a coating or anode does not significantly decrease individual scores of the carbon steel. Most coatings contain an organic component which has been produced either from petroleum or natural gas. The use of these non-renewable resources will slightly reduce the Resources to Production Ratio Score (i.e. long-term availability) from 5 to 4 (*325*). As for all products containing petroleum derived organic substances, the development of bio-based alternatives presents an interesting option for ensuring long-term availability and potentially increasing sustainability of production.

Another aspect to consider for protective coatings is that they often contain active substances which prevent the initiation of corrosion if the barrier formed by the coating is damaged. The future availability, as well as the potential environmental impact of large-scale use of these substances also needs to be taken into account prior to investing in the development of new coatings. For instance, coatings containing cerium nanoparticles have been shown to provide significant corrosion inhibition to steel substrates (*326*). Cerium reserves are however geographically highly concentrated (HHI of ca. 2250) and the use of such coatings would reduce this score for steel components from 5 to 2 (*246*). Furthermore, the extraction of cerium from mined ore is complicated and cost-intensive leading to a number of severe environmental issues (*327*). Finally, it must also be taken into account that a certain amount of cerium will leach into the environment during the lifetime of the coated component. The toxicity of cerium oxide nanoparticles is a topic of intensive investigation and initial results currently point towards the possibility of adverse effects on multiple organisms (*328, 329*). Therefore, it may be the case, that extensive use of these particles in sensitive marine environments is prohibited by governments in the future, further reducing the overall score of this improvement strategy. A more promising approach (from a resource and environmental perspective) are thermally sprayed aluminum coatings which are often employed for corrosion protection of submerged steel components (*330, 331*). Looking at the availability scores for aluminum (the element, produced from bauxite) in Table 5.4 it can be seen, that availability or concentration does not present an issue. The EI of aluminum production still needs to be taken into account, as well as the potential impact of aluminum leaching into the environment. Although higher aluminum concentration have been found to have adverse effects on certain marine organisms, it is suspected that the increase in dissolved aluminum caused by leaching from offshore structures will remain well below this level due to dilution effects (*332, 333*).

As mentioned, another main weakness of all analyzed metals is the high EI of production. The sources of these impacts are direct solid, liquid and gaseous emissions occurring during mining and processing as well as indirect emissions stemming from the production of energy and reagents required for these steps (*257*). Concerning the process of resource extraction (i.e. mining and separation of metals from minerals) there are a number of possibilities to reduce these impacts. For instance, the energy required for the mining operations could be provided from renewable sources such as bio-based fuels or electricity (from wind, solar power etc.). Another approach is the development of more environmentally friendly, bio-based or biodegradable chemicals as well as the use of specialized microbes for the extraction of the desired metals (*334–337*). However, the only true solution to decreasing the EI of metal production is to eliminate the need for mining and processing of new virgin raw materials by significantly increasing recycling rates and moving further towards to a closed loop economy (*307*). Increasing recycling rates will furthermore also mitigate the availability concerns of essential alloying elements for AA, TiA and Ni-Cu, such as chromium, nickel or vanadium.

A major challenge in the recycling of metal alloys is the efficient separation of the individual alloy types and alloying elements as well as complete removal of contaminants from the scrap metal (*338–342*). Technologies that efficiently separate different scrap automatically according to various physical and chemical properties present promising improvements for the recycling of all metals. Examples are near infrared spectroscopy, x-ray diffraction/fluorescence, laser induced breakdown spectroscopy or 3D-imaging techniques (*338, 343*). These technologies are essential, as a proper separation of individual alloys before the actual recycling step minimizes the number of different elements (i.e. impurities) in the scrap metal, greatly improving the quality of the recycled alloys (*344*, *345*). Nevertheless, for certain impurities are almost impossible to separate completely and thus need to be removed as part of the recycling process. For example, for AA the main contaminant which reduces the quality of the recycled alloy is iron. Iron content can be managed by mixing end-of-life scrap with less contaminated scrap, obtained during the manufacture of AA products (cut-offs, shavings etc.), or primary aluminum (*338*). Also, for TiA the removal of iron (Fe) and oxygen (O) impurities in scrap material presents the largest barrier to improving the recycling rate. Again, higher quality scrap (containing lower concentrations of Fe and O) is diluted with highly pure titanium sponge (which is produced from virgin materials) to ensure sufficient quality of the recycled alloy. Lower quality scrap is used to produce ferrotitanium, an alloying element used for the production of certain steels (*341*). Thus, by reducing the Fe and especially O content of TiA scrap the need for additional virgin material and down-cycling could be reduced. Technologies for removal of these contaminants are mostly still in the fundamental stage of research (*346–351*). If further development proves successfully, they could have a high commercial potential.

Consequently, the development of recycling processes which remove certain contaminants, along with on-line analytical methods for the separation of different metal alloys present high-potential research areas, which could greatly improve the economics and sustainability of metal recycling.

5.1.6 Summary

From the metal alloys analyzed in this section the carbon steels achieved the highest score followed by titanium alloys, aluminum alloys, nickel-copper alloys and finally stainless steels. For the lower ranked alloy types the higher Durability scores could not compensate for the Future Availability concerns of various specialized alloying elements (ex. Ni, Cr, V, Mo). The main weakness of carbon steels is their low corrosion resistance, which however is compensated by a low price and high availability. Based on these results a number of research areas which may improve the performance of these materials in the future could be identified. The critical research areas identified were the development of environmentally friendly protective coatings for carbon steels and improved separation and recycling technologies, in order to minimize contaminants in the recycled materials, for all metal alloys. While many such technologies already exist, they are currently still uneconomical on a large scale. Further investments into their development may in the long-term enable a significantly more sustainable use of metals not only in marine construction but also for all other areas of application.

5.2 Composites

5.2.1 Goal of Ranking

The goal of the ranking completed in this section is to assess the potential of various FRPCs for the use as structural components for sustainable marine construction in the long-term future.

5.2.2 Definition of Functional Unit

To compare the performance of the different composites used as structural materials the FU was related to the materials' compressive strengths. For each composite the FU was the amount of material required for the production of a 1 m long column with a square cross section that is able to withstand a compressive load of 5000 kN. Consequently, the compressive strength of each FRPC determines the area of the cross section and thus also the amount of material required.

5.2.3 Composition and Mechanical Properties

For the ranking completed in this section each fiber and matrix combination was evaluated as a single material. The analyzed fibers included glass fibers (GF), carbon fibers (CF), natural fibers (NF), and basalt fibers (BF), while the matrix materials included where epoxy (E), polyester (PE), vinylester (VE) and a general thermoplastic (TP) which was defined as polycarbonate for the calculations. The composite was assumed to contain continuous fibers at a fiber volume fraction of 0.5. As the mechanical properties of FRPC components depend greatly on the exact form of manufacturing (ex. pultrusion, winding, hand layup, etc.), an average value of compressive strength (established through discussions with industry experts) was assumed for all composites (Table 5.5).

Table 5.5: Mechanical strength of analyzed FRPCs with assumed fiber volume fraction of 0.5 (based on industry sources)

Fiber	Matrix	Compressive Strength [MPa]
Glass Fiber	Epoxy	600
	Polyester	420
	Vinyl Ester	600
	Thermoplastic	420
Carbon Fiber	Epoxy	1800
	Polyester	1260
	Vinyl Ester	1800
	Thermoplastic	1260
Natural Fiber	Epoxy	150
	Polyester	105
	Vinyl Ester	150
	Thermoplastic	105
Basalt Fiber	Epoxy	600
	Polyester	420
	Vinyl Ester	600
	Thermoplastic	420

5.2.4 Composite Ranking Results

The results of the material ranking are displayed in Table 5.6. CF composites achieved the overall highest scores mainly due to their high chemical resistance and mechanical strength leading to the highest Durability, Economics and Sustainability scores for each respective CF composite. The Future Availability scores are almost identical for all materials, as the main raw material of concern is petroleum or natural gas for the production of the polymer matrices. GF and BF composites perform very similarly with the BF composites achieving slightly higher Durability and Sustainability scores. However, the values for BF are largely based on estimates, as they have not been extensively used in construction to date (resulting in a lower Economics score compared to GF). Consequently, further research will be required to more precisely determine the overall performance of the BF composites in marine environments. Despite being the only fiber type that can be produced from renewable sources, the NF composites are the lowest ranked materials in this analysis. This is due to their low moisture resistance and biological resistance, as well as their relatively weak mechanical properties. While these composites may be very promising for certain applications where cheap, light-weight components are required, they are not well suited for the use as structural materials in marine environments without further protection and improving their mechanical properties. The individual attribute scores will be discussed for all analyzed composites in the following subsections.

Table 5.6: Ranking results including attribute, category and total scores of analyzed FRP composites

	Fiber	Glass				Carbon				Natural				Basalt			
	Matrix	E	PE	VE	TP	E	PE	VE	TP	E	PE	VE	TP	E	PE	VE	TP
Durability	Corrosion Resistance	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	Resistance to Biological Degradation	5	5	5	5	5	5	5	5	4	4	4	4	5	5	5	5
	Fatigue Resistance	3	3	3	3	4	4	4	4	3	3	3	3	3	3	3	3
	Resistance to Stress Corrosion Cracking	3	3	3	3	5	5	5	5	2	2	2	2	4	4	4	4
	UV Resistance	3	3	3	2	3	3	3	2	2	2	2	1	3	3	3	2
	Moisture Resistance	3	2	4	3	4	3	2	4	1	1	1	1	3	2	4	3
	Category Score	3.92	3.69	4.15	3.85	4.54	4.31	4.08	4.46	3.00	3.00	3.00	2.92	4.08	3.85	4.31	4.00
Economics & Costs	Material Costs	4	3	3	2	5	5	5	4	2	1	1	1	4	3	3	2
	Ease of Manufacture	4	4	4	3	4	4	4	3	4	4	4	3	4	4	4	3
	Maintenance Cost - Vulnerability	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Maintenance Cost - Repairability	4	4	4	3	4	4	4	3	4	4	4	3	4	4	4	3
	Reaction to Fire	3	2	3	1	3	2	3	1	1	1	1	1	3	2	3	1
	Resistance to Fire	3	3	3	1	3	3	3	1	1	1	1	1	3	3	3	1
	Performance Uncertainty	3	3	3	3	3	3	1	3	1	1	1	1	1	1	1	1
	Projected Price Developments	2	2	2	2	3	3	3	3	3	3	3	3	2	2	2	2
	Category Score	3.38	3.06	3.19	2.25	3.63	3.50	3.50	2.69	2.44	2.25	2.25	2.00	3.25	2.94	3.06	2.13
Sustainability	Raw Material Renewability	1	1	1	1	1	1	1	1	3	3	3	3	1	1	1	1
	Recycling Approach	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	Impact of Production on Human Health	3	2	4	2	5	5	5	4	1	1	2	1	3	3	4	3
	Impact of Production on Ecosystems	3	2	4	3	5	4	5	5	1	1	2	1	3	2	4	3
	Impact of Production on Resources	4	2	5	2	4	3	5	3	1	1	2	1	5	3	5	3
	Category Score	2.55	1.82	3.09	2.00	3.27	2.91	3.45	2.91	1.64	1.64	2.18	1.64	2.73	2.18	3.09	2.36
Future Availability	Short-Term Availability	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Long-Term Availability	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Geographical Distribution of Reserves	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	Potential for Restrictive Government Regulation	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	Development of Recycling Infrastructure	3	3	3	3	4	4	4	4	3	3	3	3	3	3	3	3
	Projected Growth of Competing Industries	3	3	3	3	2	2	2	2	3	3	3	3	3	3	3	3
	Ease of Production Increase	3	3	3	3	3	3	3	3	2	2	2	2	3	3	3	3
	Category Score	3.69	3.69	3.69	3.69	3.75	3.75	3.75	3.75	3.63	3.63	3.63	3.63	3.69	3.69	3.69	3.69
	Total Score	**3.42**	**3.14**	**3.59**	**3.13**	**3.81**	**3.65**	**3.73**	**3.58**	**2.82**	**2.80**	**2.94**	**2.75**	**3.49**	**3.26**	**3.62**	**3.24**
	Rank	**8**	**11**	**5**	**12**	**1**	**3**	**2**	**6**	**14**	**15**	**13**	**16**	**7**	**9**	**4**	**10**

5.2.4.1 Durability

Aside from the NF composites all materials have a high Durability score with the main weaknesses being UV and Moisture Resistance.

All FRPCs are inherently corrosion resistant and, except for the NF composites, are immune to degradation by marine organisms (score 5). The natural fibers contained in the polymer matrix could be degraded by marine organisms if they are exposed to the surrounding environment, through for instance cracking of the matrix (score 4).

The fatigue resistance of FRPCs is determined mainly by the fiber type and content. GF, BF and NF can suffer from fatigue damage. However, if stresses are kept below the fatigue limit, (which can be accurately predicted) the polymer matrix will stretch elastically leading to an infinite fatigue life (score 3) (*352*). CFs are more resistant to fatigue than the other fiber types (score 4) (*274*).

For the thermoset matrices UV radiation mainly presents a problem concerning the esthetics, as the rays can only penetrate about 1 mm into the polymer. This leads to a discoloring and roughening of the surface layer but does not strongly affect the mechanical properties of the composite if the entire component is thick enough (> 10 mm) (*267, 353*). As the degraded surface can be more easily removed by mechanical forces which would lead to the exposure of the polymer layer beneath it, UV rays can lead to a more rapid degradation of the composite (score 3 for GF, CF and BF with E, PE and VE matrix). TP is more vulnerable to UV degradation. It becomes brittle during exposure and can completely degrade over time. The time of degradation can be controlled by increasing the composites thickness (score 2 for GF, CF and BF). As NFs are degraded through exposure to UV rays, the scores were reduced for the NF composites (score 2 for E, VE, and score 1 for TP) (*354*).

The most crucial attribute determining the Durability of FRPCs in the marine environment is their moisture resistance. The polymer matrices of these composites can absorb water which can lead to swelling and also degradation of the polymer. Swelling of the matrix leads to degradation of the fiber matrix interface and thus decreases the composites mechanical properties. In general, VE has the best properties of all the matrices as it only absorbs little moisture (*355*). This also limits the amount of moisture that could potentially reach the imbedded fibers (score 4 for GF and BF). For CFs however, the CF-VE bond is inherently weak and further decreases with even slight swelling of the matrix (score 2) (*356, 357*).

Although the individual behavior is not exactly the same the E and TP matrices were seen as similar concerning moisture resistance. Swelling moderately reduces the mechanical properties of composites with these matrices. GF and BF fibers may degrade slightly over an extended period of time (score 3) while CFs are not affected (score 4) (*358*). PE, being one of the cheapest resin materials, absorbs comparably large amounts of water and is also susceptible to leaching. When used in combination with GF and BF, components should not be used in marine environments without a protective coating if longer lifetimes are desired (score 2). For CF this is less critical (score 3). For NF composites the fibers themselves completely degrade over time if exposed to moisture. Therefore, even if the matrix only absorbs a small amount of water, the mechanical properties of the component will decrease greatly over time (score 1 for all matrices) (*359*).

The susceptibility of the composites to SCC is similar to the moisture resistance rating, as it is dependent on the propensity of the fibers to be degraded by moisture if mechanical forces cause cracks in the surrounding polymer matrix. CFs will not be degraded (score 4), while NFs will degrade rather quickly (score 2). GFs are slightly more resistant but will also degrade over time if exposed to moisture (score 3) (*360*). Not much data exists on the performance of BFs. Some experts believe them to be immune, while others consider their behavior similar to GFs (score 4). Further research would allow a more exact ranking of this fiber type.

5.2.4.2 Economics and Costs

The scores for most analyzed composites are rather low in this category as they are relatively susceptible to mechanical damage as well as fire and have not been used extensively for large scale structural components in the marine environment.

While CF composites are the most expensive per kg, their superior mechanical properties greatly reduce the amount of material required for one FU and thus make them the cheapest material for this evaluation. The opposite occurs with the NF composites, which are the cheapest per kg but due to the low mechanical strength have the highest costs per FU.

There exist various techniques for the manufacture of FRPC components which depend mainly on the type of matrix and not the fiber type. Composites with thermoset matrices can be constructed rather easily by hand-layup. However, the quality of such components can be very variable and needs to be done carefully to achieve good results. For highest quality, large scale composites, layup can be done with machines followed by curing in an autoclave. Another manufacturing technique, vacuum assisted resin transfer molding (VARTM), enables the production of large parts in any shape (provided an appropriate mold is manufactured) with a high quality and curing at room temperature. In general, it may be more appropriate to manufacture composite components in a factory, but on-site fabrication is also possible (score 4 for all E, VE and PE composites). Thermoplastics on the other hand need to be heated in order to allow for the forming and bonding of a composite component. Therefore, TP composites are manufactured in a factory where the regular application of heat does not present a problem (score 3 for all TP composites).

FRPCs are rather sensitive to damage from impact as this can cause delamination. This damage can occur inside the composite and not be visible from the outside. However, due to the structure of composite materials damage remains rather local. A crack in the matrix is stopped when it reaches the next fiber interface. In general TP matrices are more ductile and can absorb larger impact forces than thermosets but the overall ranking score was not changed as the general behavior is very similar (score 3 for all composites).

If damaged, FRPCs can be replaced onsite by cutting out the damaged part and applying a new composite patch with fresh resin. This can restore a certain amount of strength. However, the fibers are cut at interface between the old and new matrix, decreasing the strength and durability of the component. The onsite application of thermoset resins is simpler than that of thermoplastics. Thus, mechanical properties can be restored more completely when repairing thermoset composites (score 4 for all E, PE and V composites and score 3 for all TP composites).

The flammability classes used to determine the composites' Reaction to Fire are dependent on the polymer material. E and VE composites correspond to class C, while PE composites fall into class D (*361–363*). As no data could be found for TP composites it was assumed that they would fall into the lowest category. All NF composites also fall into this class, as the fibers themselves are combustible (*364*). For the NF composites this also leads to the lowest score for Resistance to Fire, as both the polymer matrix and the fibers are flammable but burn at different rates and temperatures which makes it exceedingly difficult to predict their burning behavior.

The Resistance to Fire of the GF, CF and BF composites is also is limited by the relatively low degradation temperature of the polymer matrix. However, intensive research into the burning behavior of different matrix materials have made it possible to more or less accurately predict the burn and char rate of these materials. Char formation on the surface of a component protects the underlying layer of material from the heat for a certain amount of time thus increasing the lifetime of the component in a fire. Furthermore, it has been shown, that with a proper design, composite components can retain their structural integrity during a fire for an extended period of time if necessary (score 3 for E, PE and VE composites) (*237*). TP melts and degrades at low temperatures and will not be able to withstand a fire for very long. Even if the fibers remain intact as the matrix material melts away the composite will lose all mechanical strength (score 1 for all composites).

Concerning Performance Uncertainty, GF and CF composites are the only composites that have been used extensively in the construction of small and large vessels to date. However, the use as structural components in larger offshore structures has not been fully established to date (score 3). An exception are CF-VE composites which, due to the mentioned weak interfacial bond, have not found any significant application in marine environments (score 1). The same is true for NF and BF composites. Although tests concerning the durability in humid environments have been conducted (*270*, *271*, *354*, *365*, *366*), and the assumption by most experts that BF will perform similarly to GF in marine use, the real life performance uncertainty for these composites is very high (score 1 for all matrices).

The Projected Price Developments are dependent on the change in prices of the fibers as well as the polymer matrices. In general, it is expected that prices for petroleum-based products will increase in the future. This will also be affected by governments and politics by influencing the price of crude oil through tariffs, taxes and trade restrictions. Considering the already low prices for GF it is very unlikely that the production of GF will become any cheaper in the future. The same is true for BFs, which are even cheaper to produce (score 2 for all GF and BF composites). The processes for CF production and CF composite production are however still being further optimized. Nevertheless, CF prices have not decreased strongly in the past years despite predictions that they could reach the price of GF at some point. Therefore, although a slight decrease in price is possible with further development of production and processing technologies, it is not expected that the prices for CF will decrease greatly in the future (score 3 for all matrices). Finally, as NF composites are currently still being produced on a relatively small scale, a large increase in production volumes which is expected in the longer term for these materials may lead to economies of scale and thus reduced production costs for manufacturers. Further process developments may also decrease the production costs for the fibers (score 3 for all matrices).

5.2.4.3 Sustainability and Environmental Impact

Aside from those containing NF (which contain 50% fibers that are considered renewable, score 3), none of the analyzed composites is produced from renewable raw materials (score 1). Further decreasing the overall Sustainability scores for all composites, are the very low recycling rates. Currently, no technology exists to fully recycle FRPCs, especially with a thermoset matrix, as the resin cannot be uncured once hardened. Therefore, downcycling is the only disposal option beside incineration or landfilling. For downcycling the composite is ground into fine powder and used as filler in concrete or other composites. Although it may be possible to melt thermoplastic matrices and recover the fibers this is currently only done on a laboratory scale and the mechanical properties of the recovered fibers are strongly degraded (*367*, *368*). In Europe downcycling is more common than in the US where incineration and landfilling are still the major disposal options (score 2 for all composites).

The EIs of the individual composites were calculated using data from the Ecoinvent 3.3 database, which was adapted with data from literature to reflect the exact fiber and matrix type, as well as the fiber volume fraction specified earlier (information on the individual calculations can be found in Appendix B). Overall the CF composites have the lowest EI/FU followed by the BF composites which are slightly better than the GF composites (Table 5.7). The lowest ranking materials are the NF composites. This is due to the relatively low mechanical strength of the NFs leading to a large amount of material required for a FU. Per kg the NF composites produce a lower EI than those with GF. Contrarily the CF composites have an EI of production that is almost three times higher per kg than that of the corresponding GF composites. Concerning the polymer matrices, they all have very similar impacts per kg. However, factoring in the contribution to the overall compressive strength, VE performs best, followed by E, PE and TP if ranked in relation to the FU.

Table 5.7: Mass, price and EI data of analyzed FRPC materials (based on data from 296, 369 and own EI calculations shown in Appendix B)

Fiber	Matrix	kg/FU	Price [$/FU]	Environmental Impact [Pt/FU]			
				Human Health	Eco-systems	Resources	Total
Glass Fiber	Epoxy	15.96	485.7	4.29	1.72	3.30	9.32
	Polyester	22.59	572.5	5.51	2.69	4.18	12.38
	Vinyl Ester	15.08	573.2	3.70	1.55	2.97	8.22
	Thermoplastic	22.47	671.3	5.77	2.52	4.13	12.43
Carbon Fiber	Epoxy	4.27	155.9	2.65	1.14	3.18	6.98
	Polyester	6.03	213.0	2.80	1.43	3.87	8.10
	Vinyl Ester	3.98	158.8	1.90	0.93	2.70	5.53
	Thermoplastic	5.99	218.7	2.93	1.40	3.92	8.25
Natural Fiber	Epoxy	44.25	942.8	10.35	5.49	8.63	24.47
	Polyester	62.38	1106.7	12.35	8.73	10.23	31.32
	Vinyl Ester	40.75	1084.0	8.07	4.81	7.34	20.21
	Thermoplastic	61.90	1294.6	13.37	8.11	10.15	31.63
Basalt Fiber	Epoxy	16.46	501.0	3.83	1.68	3.18	8.69
	Polyester	23.30	590.6	4.87	2.63	4.01	11.51
	Vinyl Ester	15.58	592.2	3.27	1.52	2.85	7.64
	Thermoplastic	23.18	692.6	5.12	2.46	3.96	11.55

5.2.4.4 Future Availability

The Future Availability scores are very similar for all analyzed composites, as petroleum (or alternatively natural gas), required for production of the polymer matrices as well as the CFs is the only critical raw material. Table 5.8 shows the availability and concentration values for these resources.

Table 5.8: Availability and geographical concentration of oil and natural gas (Calculated with data from 325)

Resource	Short-Term Availability (Reserves / Production Ratio)	Long-Term Availability (Resource / Production Ratio)	Geographical Distribution HH-Index of Reserve Concentration
Oil	50.7	128	957
Natural Gas	52.8	115	998

The petroleum-based materials (resins and CF) are also the reason for the slightly reduced Government Regulation score of all composites (score 4). In the past governments have already banned certain chemicals from being used, after it had been shown that they can have severe negative effects on human health or the environment. Although the substances used for the manufacture of the polymers and CFs which are being analyzed in this ranking have been used intensively for years there is a small possibility that more stringent environmental regulations will restrict their use. Furthermore, as petroleum is a limited resource, there is a chance that governments may impose regulations to control its use, in light of increasing scarcity. Most likely however the use of petroleum as a fuel will be restricted before the manufacture of high-quality products, such as polymers, is affected. Concerning the materials required for the production of GF and BF there is no reason why governments should forbid any specific mining practices as the rock mining which takes place does not involve any strongly hazardous chemicals.

The long-term recycling potential of all composites (except for the CFs) is rather moderate. While the percentage of composites which will be downcycled in the future will definitely increase, the step towards full recycling is very unlikely for GF, NF and BF, especially with the matrices investigated here. The processes which are currently running on pilot plant scale for the full recycling of continuous fiber composites involve pyrolysis or chemical treatment to dissolve the matrix. As these methods are extremely aggressive, the fibers degrade to a point where they cannot be used in the same applications again. For GF and BF additionally the price of production is very low and therefore the pressure to develop new recycling methods is also not very high. A promising approach for these fibers is to use chopped composite pieces as feed for cement kilns. The high calorific value of the resins provides heat for clinker production while the mineral content of the fibers (calcium carbonate, alumina, silica) is recycled into cement clinker. Thus, this can be seen as a type of cross material recycling. However, full recycling of long GF and BF for reuse in composites will not be possible in the foreseeable future (score 3). For NF, the possibility of composting would mean that they could be considered as fully recycled. However, as mentioned, it is not possible to remove the fibers from the polymer matrices and therefore even composites with NFs will be treated in the same way as those with GF and BF making downcycling the only option (score 3). A possibility for full recycling would be the development of fully biodegradable, bio-based composites by using a matrix which was also produced from biological sources. However, these bio-based plastics are currently not durable enough to be used in structural applications (*370*). For CF composites, full recycling is potentially possible (score 4). CFs can withstand the aggressive processes for removal of the matrix material without being fully degraded. Nevertheless, currently the recycled CFs lose around 50% of their strength during their recycling process so they cannot replace virgin fibers. However, further research is ongoing to improve this process and retain a larger proportion of the fibers' mechanical strength (*367, 368, 371*). An additional approach which has been proposed, is the development of new thermoset resins which can be uncured with specific chemicals. This is currently only being investigated in the lab and is still a long way from commercial production.

Whether competition from other industries will be significant in the future is uncertain for all but the CF composites. The construction industry is not yet a major user of CF composites accounting for only 5% of total demand. The three largest industries are aerospace and defense (30%), automotive (22%) and wind turbines (13%). Demand is expected to increase strongly for all these sectors, for instance due to increasing pressure from governments and also society for lower emission vehicles requiring light-weight alternatives to steel. Demand from the construction industry is still far below the expected potential. This is mostly due to the high price of CF composites compared to steel and in some countries building code requirements limiting the use of structural FRPC components. However, even with increasing demand growth in the construction sector it is still expected to remain a rather small percentage of global CF composite demand in the future. In the past it has already happened that a strong increase in CF demand from the aerospace industry caused a scarcity in the market for other segments. It is likely that this will occur again in the future despite the addition of significant production capacity by producers (score 2) (*372, 373*).

The main concern for the GF, NF and BF composites comes from the use of oil for the manufacture of the matrix material. Currently, only a small percentage of raw oil is used for the manufacture of high value chemicals and plastics, while the main use is as fuel. This distribution will definitely shift further towards the chemical and plastic sector as the resource becomes scarcer. The global demand for plastic is expected to increase rapidly, especially due to economic development in emerging countries. As composite resins only account for a small part of the overall plastics and chemical industry, it may be possible that in the long-term future the limited petroleum resources are diverted to produce other products. For the use of the FRPCs themselves, no strong competition is expected for these fiber types. The transport and construction industries are the major consumers of GF composites. Each sector is responsible for about one third of total demand. The demand from the transport industry for light-weight GF components will likely increase in the future. The construction industry is also expected to be one of the strongest growing demand sources as more and more building codes are adapted to allow the replacement of more traditional materials such as steel with GF composites for certain applications (score 3) (*373*). BF composites serve mainly the same markets as GF composites. In general, the use of BF is currently still limited compared to GF or CF, as it is a relatively new material. The main demand growth is expected from similar industries as for GF composites which are the transport and construction industries. Depending on the results of further research on the durability of these fibers, the marine industry may also become a major customer. As the raw materials for the production of BF and GF are abundantly available around the globe there should not be any large competition for these materials from the different industries (score 3). For NF composites the largest market is currently the automobile sector. As mentioned, it is expected that this sector will continue to grow at above average rate and remain the main demand driver for natural fiber composites. The construction industry is the second largest user of natural fiber composite materials and is also expected to exhibit a high level of demand growth in the coming years (score 2) (*374, 375*).

Significantly increasing global production levels will be most challenging for NF composites. The manufacture of NF for the use in polymer composites is rather new and a strong increase in production requires a scale-up of the current process involving a certain extent of technological development. Furthermore, the supply of plants for production of fibers would also need to be increased (score 2). In the short term, CF, GF and BF supply and demand forecasts are more or less balanced. However, it is already expected that more capacity will need to be installed to meet longer term demand (*372*). Therefore, for a major increase to multiple levels of today's production new facilities would be required (score 3). While, the technology for manufacturing CF and GF is mature, the large-scale manufacture of BF is comparatively new. However, the process is very similar to the manufacture of GF (*376*). Thus, it can be assumed that scale-up should not be such a big issue and can profit from the maturity of the GF production process. Increasing the supply of polymer resins would not present an issue. The petroleum industry would have the capacity increase production if it is required and the chemical industry in turn would also be able to increase the production of the polymer resins. The technologies for the production of the thermoset and thermoplastic resins are also mature and already today produce at extremely large scales.

5.2.5 Improving NF Composite Performance

As can be seen in Table 5.6, the NF composites, which are promising materials from an availability perspective and have the lowest costs and EI per kg, achieve the lowest scores of all composites mainly due to their low mechanical strength. While they also suffer from low moisture resistance and high flammability, these weaknesses are also critical for the other fiber types. Therefore, focusing specifically on increasing the strength of these NF composites would be highly beneficial for their overall performance as this would increase their scores for the material cost and EI attributes. This is illustrated in Table 5.9 which shows how the NF composites would rank if their properties were increased to values comparable with the other composites. If the compressive strength of the NF composites could be increased to the level of the corresponding GF/BF composites, they would be ranked higher than both other fiber types for all matrices except VE, despite still suffering from the other mentioned weaknesses. CF composites remain superior and it is very unlikely that NF composites will ever reach similar mechanical properties as CF composites. If the moisture and consequently the SCC resistance of the NF composites could be increased to the values of the corresponding GF or even BF composites some of the NF composites would achieve an overall slightly higher rank. However, they would still remain the lowest ranked fiber option for each individual matrix material. Increasing the reaction to fire and resistance to fire attributes would have the smallest effect, as only the scores, but not the ranks would be increased.

A major issue affecting the mechanical strength of NF composites is the low bonding strength between the polar fibers and non-polar polymer matrices. Various physical and chemical surface treatments have been investigated to alter the fiber surface and increase the strength of the interfacial bond (*367, 377*). While these treatments have been shown to increase the mechanical strengths of the resulting NF composites, it must be kept in mind that the increased amount of energy (for physical treatments) and use of potentially harmful substances (for chemical treatments) will also increase the EI of production per kg. However, if the increase in strength is sufficient, the EI per FU of NF composites could nevertheless be decreased even to bellow the value of GF production (*378*).

Table 5.9: Effect of improving NF composite properties (red and green ranks represent a decrease resp. increase in rank)

	Fiber	Glass				Carbon				Natural				Basalt			
	Matrix	E	PE	VE	TP	E	PE	VE	TP	E	PE	VE	TP	E	PE	VE	TP
Original Ranking	Score	3.42	3.14	3.59	3.13	3.81	3.65	3.73	3.58	2.82	2.8	2.94	2.75	3.49	3.26	3.62	3.24
	Rank	8	11	5	12	1	3	2	6	14	15	13	16	7	9	4	10
NF strength equal to GF/BF	Score	3.31	2.98	3.39	2.92	3.72	3.56	3.68	3.49	3.37	3.12	3.42	3.11	3.33	3.05	3.43	3.03
	Rank	10	15	7	16	1	3	2	4	8	11	6	12	9	13	5	14
Moisture/SCC resistance equal to GF	Score	3.42	3.14	3.59	3.13	3.81	3.65	3.73	3.58	2.98	2.9	3.15	2.9	3.44	3.26	3.62	3.24
	Rank	8	12	5	13	1	3	2	6	14	16	11	15	7	9	4	10
Reaction/Resistance to Fire equal to GF	Score	3.42	3.14	3.59	3.13	3.81	3.65	3.73	3.58	2.89	2.85	3	2.78	3.44	3.26	3.62	3.24
	Rank	8	11	5	12	1	3	2	6	14	15	13	16	7	9	4	10

5.2.6 Summary

Overall, the best ranked materials in this section are the CF composites followed by BF and GF composites. The lowest scores were achieved by NF composites mainly due to their low mechanical strength and lower chemical resistance. Concerning the matrix material, E and VE show a similar performance followed by the cheaper and less resistant PE and TP resins. Using the results from the presented ranking, the main weaknesses of the NF composites were discussed, and the improvement of mechanical strength was identified as the most promising development area to increase the overall performance of these composites. Naturally, there exist many further research areas aiming at improving the performance of composites with all fiber types for the use in marine construction, such as increasing moisture and fire resistance. These research areas will be essential to develop composites that are stable and durable in the extreme conditions present in the marine environment.

5.3 Cement and Concretes

5.3.1 Goal of Ranking

The goal of the evaluation completed in this section is to rank different concrete and rebar types according to their potential use for sustainable construction in the marine environment in the long-term future.

5.3.2 Definition of Functional Unit

In order to compare the performance of different concrete and rebar types, FU of the analysis was related to the materials' compressive strengths. A measure based on a commonly used standard for measuring concrete compressive strength was used. For each type of concrete, it was calculated how many 150 mm cubes would be required to carry a mass of 1225 kN (1 cube = 50 MPa compressive strength).

5.3.3 Composition and Mechanical Properties

For each cement type the compressive strength of the resulting concrete is strongly dependent on the final mix composition. Therefore, a specified mix composition with a corresponding compressive strength was used for all evaluations (Table 5.10). Although the type of aggregate also influences the quality of the concrete, its exact composition can vary strongly depending on the location it was sourced from. Therefore, aggregate was simply separated into fine aggregate (sand) and coarse aggregate (gravel). While rebar is introduced into concrete to increase its tensile strength, it does not greatly affect the overall compressive strengths of the material. For the EI and price calculations however, it was necessary to include the amount of rebar required per FU, as well as the composition of the rebar. As the strength/weight ratio of the different materials varies, the recommended amount of rebar is dependent on the rebar type (Table 5.11).

Table 5.10: Compressive strength and mix compositions of analyzed concretes

Cement Type	Compressive Strength [MPa]	Concrete Mix Component (kg/m^3)
Blended[A]	50	OPC (190), GBFS (190), Water (152), Gravel (960), Sand (806)
Alkali Activated[B]	50	FA (444), 30%-NaSi-Solution (111), NaOH (17.8), Water (25.8), Plasticizer (6.1), Gravel (1170), Sand (630)
Calcium Sulfoaluminate[C]	45	CSA Cement (360), Water (152), Gravel (960) Sand (806)

A: (*252, 379*), B: (*288*), C: (*289, 380*)

Table 5.11: Rebar composition and recommended reinforcement amount (291)

Rebar Type	Recommended wt% in Concrete	Rebar Composition
Carbon Steel	4	Fe (>99 wt%)
Duplex Stainless Steel	4	Fe (balance), Cr (22 wt%), Ni (5 wt%), Mo (3 wt%), Mn (2 wt%)
Glass Fiber Reinforced Polymer	0.8	E-Glass Fiber (50 vol%), Epoxy Resin (50 vol%)
Carbon Fiber Reinforced Polymer	0.2	High Strength Carbon Fiber (50 vol%), Epoxy Resin (50 vol%)

5.3.4 Concrete Ranking Results

Table 5.12 shows the result of the ranking of the different combinations of concrete and rebar types. All concretes have a high durability and good economic performance. The main differences of the individual materials stem from the Sustainability and Future Availability scores. The highest scores are achieved by AAC and BC with CFRP rebar followed by CS and GFRP rebar. While overall the scores for AAC and BC are very similar, CSA concrete scores lower for all rebar types due to higher costs, a higher overall impact of production and availability concerns related to the increased aluminate mineral demand (i.e. bauxite). As can be seen the scores for CFRP rebar are higher than those for CS regardless of the cement type. Thus, the higher price of CFRP rebar is outweighed by the increased durability and also the smaller amount of rebar required due to the increased strength/weight ratio. GFRP and CS rebar achieved very similar scores overall showing that the reduced economics score is compensated by the increase in durability and vice versa. The lowest ranking rebar type was by far SS, mainly due to the high EI of production and issues associated with the future availability of specific alloying elements which cannot be compensated by the increase in durability. The reasoning behind the individual scores will be discussed in detail in the following subchapters.

Table 5.12: Attribute, category and overall scores for analyzed concretes

	Cement Type	**Blended**				**Alkali Activated**				**Calcium-Sulfoaluminate**			
	Rebar	**CS**	**SS**	**GFRP**	**CFRP**	**CS**	**SS**	**GFRP**	**CFRP**	**CS**	**SS**	**GFRP**	**CFRP**
Durability	**Corrosion Resistance**	4	5	5	5	4	5	5	5	3	5	5	5
	Resistance to Biological Degradation	5	5	5	5	5	5	5	5	5	5	5	5
	Fatigue Resistance	4	4	4	4	4	4	4	4	4	4	4	4
	Resistance to Stress Corrosion Cracking	3	4	4	5	3	4	4	5	3	4	4	5
	UV Resistance	5	5	5	5	5	5	5	5	5	5	5	5
	Moisture Resistance	5	5	4	5	5	5	4	5	5	5	4	5
	Category Score	4.38	4.77	4.54	4.92	4.38	4.77	4.54	4.92	4.15	4.77	4.54	4.92
Economics & Costs	**Material Costs**	5	2	3	4	5	2	2	4	4	1	1	3
	Ease of Manufacture	5	5	4	4	5	5	4	4	4	4	3	3
	Maintenance Cost - Vulnerability	4	4	4	4	4	4	4	4	4	4	4	4
	Maintenance Cost - Repairability	4	4	4	4	4	4	4	4	4	4	4	4
	Reaction to Fire	5	5	5	5	5	5	5	5	5	5	5	5
	Resistance to Fire	4	4	4	4	5	5	5	5	3	3	3	3
	Performance Uncertainty	4	4	2	3	2	1	1	1	2	1	1	1
	Projected Price Developments	3	2	3	3	5	4	5	5	4	3	4	4
	Category Score	4.31	3.69	3.75	4.00	4.44	3.75	3.75	4.13	3.88	3.19	3.19	3.56
Sustainability	**Raw Material Renewability**	1	1	1	1	1	1	1	1	1	1	1	1
	Recycling Approach	2	3	1	1	1	1	1	1	1	1	1	1
	Impact of Production on Human Health	3	2	4	5	2	1	4	5	2	1	3	4
	Impact of Production on Ecosystems	3	2	4	5	2	1	4	5	2	1	3	4
	Impact of Production on Resources	3	2	5	5	2	1	3	4	2	1	4	4
	Category Score	2.36	2.09	2.82	3.18	1.55	1.00	2.45	3.00	1.55	1.00	2.27	2.64
Future Availability	**Reserves / Production Ratio**	3	1	3	3	3	1	3	3	3	1	3	3
	Resources / Production Ratio	5	2	4	4	5	2	4	4	5	2	4	4
	Geographical Distribution of Reserves	4	1	5	5	4	1	5	5	4	1	4	4
	Potential for Restrictive Government Regulation	5	2	4	4	4	2	4	4	3	2	3	3
	Development of Recycling Infrastructure	4	4	3	3	4	4	3	3	4	4	3	3
	Projected Growth of Competing Industries	1	1	1	1	3	1	3	3	1	1	1	1
	Ease of Production Increase	1	1	1	1	2	2	2	2	3	3	3	3
	Category Score	3.63	1.88	3.31	3.31	3.81	1.94	3.63	3.63	3.50	2.00	3.13	3.13
	Total Score	**3.59**	**2.88**	**3.55**	**3.77**	**3.47**	**2.64**	**3.58**	**3.86**	**3.22**	**2.59**	**3.27**	**3.51**
	Rank	**3**	**10**	**5**	**2**	**7**	**11**	**4**	**1**	**9**	**12**	**8**	**6**

5.3.4.1 Durability

As mentioned all analyzed concretes have a very high durability. BC and AAC had exactly the same scores for all rebar types, while CSA achieved a slightly lower score for CS rebar. Concerning the rebar CFRP rebar had the highest durability followed by SS, GFRP and finally CS.

All concretes are unaffected by UV radiation (score 5) and also immune to damage from marine organisms (score 5). They all exhibit very good fatigue performance (score 4). Concrete (regardless of cement type) can be degraded by moisture and also corrosive processes. Leaching (i.e. the dissolution of soluble mineral phases in the concrete matrix) leads to growing pores in the concrete and increases its susceptibility to further damage. Concerning corrosion, especially sulphates can react with calcium and aluminate phases in the concrete to form ettringite. The expansion which occurs during ettringite formation can increase the pressure in the concrete matrix and lead to cracking (*178*). Nevertheless, with a proper mix design these processes will be extremely slow and will therefore not be the limiting factor for the lifetime of a structure. Therefore, the Moisture, Corrosion and SCC Resistance scores were mainly dependent on the type of rebar in the concrete.

GFRP rebar is the only rebar type that is affected by moisture as it may be degraded through osmotic processes if enough moisture penetrates the concrete and reaches the rebar (score 4 for all cements with GFRP rebar, 5 for the other rebar types) (*381*).

GFRP and CFRP rebar is completely corrosion resistant (score 5 for all cement types). While SS rebar is not completely immune to corrosion damage, component lifetimes of 100 years were considered realistic by all participating experts (score 5 for all cements). For CS rebar the experts considered a lifetime of 50 years to definitely be possible in the marine environment. Some consider a lifetime of 100 years to be possible with careful mix design and sufficient cover. Other were less optimistic and consider 50-75 years to be the limit before corrosion damage sets in (score 4 for BC and AAC). CSA concrete is more susceptible to volume change during hydration, which can, if not addressed properly, lead to cracks and a quicker ingress of chloride. Furthermore, the pH of CSA concrete is lower than for the other concrete types (*382*). This leads to a weaker passivation of the steel rebar during the early age of the concrete and consequently a reduced resistance to corrosion. Consequently, for CSA concrete with CS rebar the Corrosion Resistance score was slightly lower than for the other cement types (i.e. 3).

For SCC resistance, the scores were the same for all cement types and only dependent on the rebar type. CFRP rebar is viewed as immune to any form of SCC (score 5 for all cement types).

CS rebar is the most susceptible to SCC (score 3 for all cement types). While far more resistant, SS rebar is not completely immune to damage from SCC (score 4 for all cement types). Finally, GFRP rebar can also be damaged through the combined effect of mechanical damage and corrosion. If the concrete cracks, as mentioned moisture can reach the rebar and degrade it. Furthermore, if the coating on the GFRP rebar is damaged the alkaline environment in the concrete will also degrade the fibers (score 4 for all cement types) (*383*).

5.3.4.2 Economics & Costs

All analyzed concretes show a similar performance for most of the attributes covered in the Economics & Costs category. The main differences are total costs, the higher performance uncertainty of the alternative cement and rebar types, as well as the Projected Price Developments and Fire Resistance.

The cost of producing 1 FU of the different cement types is very similar (Table 5.13). Although the CSA cements are slightly more expensive than BC or AAC, the overall costs are largely determined by the type of rebar used. CS rebar is by far the cheapest, followed by CFRP (due to the lower amount of reinforcement required), GFRP and finally SS which costs about 3 times more.

The versatility and robustness of concrete is one of the reasons, why it is the most used construction material on earth. This is reflected in the high scores for Vulnerability (4 for all concretes) and Repairability (4 for all concretes), as well as Ease of Manufacture. For all cement types the formwork for the final shape of the concrete can be made on site and is generally not limited concerning size or shape. BC can also be poured and prepared by untrained workers. For pure BC concrete the score would be a 5. However, the rebar type still needs to be considered. CS and SS rebar can be premanufactured in a factory and if required reshaped or cut on site with rather basic equipment (score 5). GFRP and CFRP rebar can only be prepared in factory and the exact specifications of the rebar shape and size required need to be known before production. Thus, the flexibility is limited compared to CS or SS (score 4). The same values were given to AAC, although some differences need to be mentioned. AAC is more complex to mix and pour than BC and may sometimes require heating in order to fully cure. The alkali activator can be hazardous to human health and should only be handled by trained personnel. However, some activator solutions are not any more hazardous than fresh OPC paste. Therefore, with proper training on-site fabrication is possible and with a proper mix design casting should also not present a problem. For CSA the scores were slightly reduced for all rebar types due to the fact that this cement type is also more complex to mix and pour than BC and few guidelines exist on how to achieve a durable concrete mix for specific environments, making it imperative that trained and experienced workers handle the mix design and pouring (score for CS and SS rebar 4, for GFRP and CFRP 3).

All concretes are non-flammable materials and therefore achieve the highest score (i.e. 5) for Reaction to Fire. The Resistance to Fire however varies depending on the cement type. Concrete is generally stable even at high temperatures and provides a good barrier to heat due to its low thermal conductivity. There are examples of concrete structures from BC that retained their structural integrity during fires lasting over 7 hours (*384*). The main problem which may occur is spalling due to the evaporation of water which is bound in the cement matrix. The main phase which is affected is ettringite as it contains a high number of bound water molecules. By carefully controlling the water content in the concrete a high fire resistance can be achieved. However, the exact processes that cause spalling are very complex and not easy to predict. Therefore, despite the very high resistance to fire, the unpredictability of spalling reduces the ranking of BC with all reinforcement types to 4. Due to the different phase composition of the matrix, less water is present in AAC concrete making it less susceptible to spalling. In fact, AAC concrete panels were found to withstand temperatures of over 800 °C for 4 h without significant damage or spalling (score 5) (*385*). The opposite is true for CSA concrete. CSA concrete has a far higher ettringite content in the matrix than BC. On the one side this is good if CSA concrete components are used in non-structural cladding. In this case, the energy of a fire does not immediately heat up surrounding material but is diverted to evaporate the water in the concrete. However, if CSA elements are used for structural purposes this presents a problem as the ettringite phase decomposes when the water is lost. This leads to the concrete becoming more porous and a consequent loss of mechanical strength and possible collapse if a sufficient amount of water evaporates (*386, 387*). Due to the unpredictability of the rate and amount of strength loss a value of 3 was seen as appropriate for all reinforcement types.

While this may change in the future, the performance uncertainty of all alternative cements and also rebar types is currently still relatively high leading to low scores for these materials. Only concrete from BC with CS and SS rebar has been used for decades in the industry. Extensive building codes exist and the use of these materials for marine construction is well established. However, the blended cements used today differ strongly from those employed 50 years ago, when many of these regulations were written. The new BCs still fit into the old classification due to their similar composition, so they can be used under the same codes. However, no long-term data exists for the use of the newer BCs (as they have only been developed in the 80s and 90s) (*277*). Nevertheless, most experts are confident in the performance of these BCs (score 4 for CS and SS rebar). CFRP rebar is currently being tested in multiple larger structures globally and codes exist for smaller structures (score 3) (*291*). GFRP rebar has been used less extensively than GFRP (score 2). AAC has only been used for large scale commercial construction on land in certain countries, such as Australia, Ukraine and Russia (*278*). While research data on the performance of this cement type in the marine environment exists, no codes or standards have been produced yet (*388*). Furthermore, no data exists on the use of any reinforcement type except steel (score 2 for CS rebar and 1 for all other rebar types) (*282*). The same scores were given to CSA concrete (*279*).

Finally, for the projection of future price development the prices of the rebar and the cement were considered for all materials. For the rebar no significant changes in price are expected for CS, GFRP and CFRP. Only the price for SS is expected to increase strongly due to rising raw material prices (*302, 306*). Thus, the addition of CS, GFRP or CFRP will not have any effect on the score of the different cement types, while the use of SS rebar will slightly decrease the score. For BC no great changes in price are expected (score 3 for CS, GFRP, and CFRP rebar and score 2 for SS rebar). As AAC concretes are still in development and full commercialization has only begun in many countries, it is expected that as demand and production volumes increase significant economies of scale can be achieved. This would naturally lead to a decrease in price for the cement and the corresponding concrete (score 5 for CS, GFRP, and CFRP rebar and score 4 for SS rebar). CSA concretes are also still in the early stages of commercialization. Increasing demand and production volumes may well enable the industry to achieve significant economies of scale and thus reduce costs of the CSA cement. However, this development is counteracted by the expected price increases for bauxite (*302*). As the expected increase in bauxite price is only around 30% it is expected that the total price for CSA concrete will decrease slightly in the future (score 4 for CS, GFRP, and CFRP rebar and score 3 for SS rebar).

5.3.4.3 Sustainability

In comparison with other materials the production of concrete has relatively low environmental impacts (Here they are ranked relative to one another). Nevertheless, the overall Sustainability scores of all analyzed concretes are rather low, as none of the used raw materials are renewable (score 1 for all materials) and global recycling rates are very low.

Concrete can be ground up and reused as aggregate in new concrete or for road construction. However, this is only done to a limited extent and only for concrete made with BC. Respondents from the US rated the amount of downcycling of concrete as lower than those from Europe. For SS rebar recycling is economically feasible due to the higher price of the raw materials. For CS it would make sense from an environmental perspective, but it is not done very often, as it is not economically viable at current steel prices and the cost of removing rebar from solid concrete. For GFRP and CFRP rebar an option would be to grind up the rebar and use it as filler in other composite materials or concrete. However, as they aren't used often these rebar types are currently mostly landfilled. Combining the main disposal route that is actually used for the concretes with the respective rebar types resulted in the BC scores shown in Table 5.12. No recycling infrastructure specifically for AAC concrete exists to date and recycling is only being done on a lab scale (score 1 for all rebar types). The potential for recycling of this concrete type is however similar to that for BC concrete. Also, for CSA concrete no recycling infrastructure specifically for this concrete type exists (score 1 for all rebar types).

The individual EIs were calculated for the production of 1 FU of the specific concrete using data from the Ecoinvent 3.3 database which was adapted with data from literature to accurately represent the concretes specified for this evaluation (information on the individual inventories can be found in Appendix B).

Despite OPC being associated with higher CO_2 emissions during production, the BC cements show the lowest EIs of the three analyzed cements. While the use of FA as the main constituent for AAC cement leads to almost no impact, this is outweighed by the impacts caused by production of the activator solution, thus leading to a slightly higher EI than for the corresponding BCs. The value for the CSA cements is the highest of all due to the fact, that no SCMs are used in the analyzed mix. Production of the CSA cement itself has a 12% lower EI than pure OPC. However, compared to the analyzed BC with 50% GBFS the EI is still almost 30% higher. This underlines the importance of combining the different approaches described in section 1 to reduce the overall impact of cement production.

Concerning the rebar, the use of CFRP rebar is associated with the lowest overall impacts followed by GFRP, CS and finally SS. As the production of CFRP and CFRP rebar has an EI that is significantly higher than that of CS (CFRP 4x higher, GFRP 2x higher), the lower EI values for the concrete are solely due to the lower recommended amount of reinforcement needed for the FRP rebar. SS has the highest EI of all rebar types due to the processing of the different mineral ores (i.e. nickel, chromium, molybdenum) required for production of the duplex alloy.

Table 5.13: Mass, price and EI per FU of analyzed concretes (based on data from 296 and own EI calculations shown in Appendix B)

Cement	Rebar	kg/FU	Price [$/FU]	Environmental Impact [mPt/FU]				% of EI caused by Rebar
				Human Health	Ecosystems	Resources	Total	
Blended Cement	Steel	8.1	0.97	69.7	29.4	57.1	156.2	60%
	Stainless Steel	8.1	2.8	1182.6	67.9	850.5	2101	97%
	GFRP	7.82	2.55	47.8	22.8	28.2	98.8	37%
	CFRP	7.78	1.36	40.6	20.2	26.8	87.6	27%
Alkali Activated Cement	Steel	8.1	1.01	75.2	30.3	67.9	173.4	54%
	Stainless Steel	8.1	2.84	1191	68.8	860.2	2120	96%
	GFRP	7.82	2.59	53.3	23.7	38.9	115.9	32%
	CFRP	7.78	1.4	46	21.2	38.5	105.7	22%
Calcium Sulfoaluminate Cement	Steel	9	1.08	85.8	37.4	63.4	186.6	56%
	Stainless Steel	9	3.11	1323	80.3	945	2348.3	96%
	GFRP	8.69	2.84	61.4	30.2	31.2	122.7	33%
	CFRP	8.64	1.51	53.4	27.3	29.7	110.4	24%

5.3.4.4 Future Availability

The Future Availability scores for the analyzed concretes are determined by the raw materials required for their production. In almost all cases the most critical resource (i.e. the raw material with the lowest attribute score) is a component of the rebar and not the cement. Although there may exist local deficiencies of limestone, clay, gravel, sand or water required for concrete production, this is not the case on a global level and therefore these resources are seen as abundant. Table 5.14 shows the critical raw materials for each cement and rebar combination, as well as the corresponding availability and concentration values.

Next to the materials shown in Table 5.14 there are further components of each cement type the strongly influences the remaining Future Availability attributes. These are GBFS for BC, FA and the activator for AAC and bauxite for CSA.

For the raw materials required for the production of BC there are no real competing industries, as the sheer amount of cement and concrete produced globally for construction dwarfs all other industries and uses. However, already today the amount of GBFS produced is not sufficient to meet demand. It is expected that, as steel production from blast furnaces diminishes due to increased recycling and use of alternative production technologies, the availability of GBFS will also be reduced and remain at a level of about 8% of global cement production (*233*).

Therefore, as demand from the construction industry alone will exceed the global supply level for GBFS and an increase in production can only be achieved in combination with an increase in steel production, BC scored the lowest value (i.e. 1) for the Demand from Competing Industries and Ease of Production Increase attributes for all rebar types.

Table 5.14: Critical raw materials for analyzed concretes (data calculated using 246 and 325)

Cement & Rebar Type	Reserve/Production Ratio		Resource/Production Ratio		HHI of Reserves	
	Raw Material	Years	Raw Material	Years	Raw Material	Value
BC/AAC & CS	Iron Ore (Rebar)	60	Iron Ore (Rebar)	170	Iron Ore (Rebar)	1586
CSA & CS	Iron Ore (Rebar)	60	Iron Ore (Rebar)	170	Bauxite (Cement)	1538
BC/AAC/CSA & SS	Chromite (Rebar)	17	Nickel (Rebar)	58	Chromite (Rebar)	>2500
BC/AAC & GFRP	Petroleum (Epoxy Resin - Rebar)	50	Petroleum (Epoxy Resin - Rebar)	130	Petroleum (Epoxy Resin - Rebar)	<1000
CSA & GFRP	Petroleum (Epoxy Resin - Rebar)	50	Petroleum (Epoxy Resin - Rebar)	130	Bauxite (Cement)	1538
BC/AAC & CFRP	Petroleum (Epoxy Resin - Rebar)	50	Petroleum (Epoxy Resin - Rebar)	130	Petroleum (Epoxy Resin - Rebar)	<1000
CSA & CFRP	Petroleum (Epoxy Resin - Rebar)	50	Petroleum (Epoxy Resin - Rebar)	130	Bauxite (Cement)	1538

For AAC concrete the activator and the solid precursor in the form of FA present the main issues concerning governmental regulations, competition and ease of production increase. FA is a byproduct of power production in coal fired power plants. Many advanced economies have already developed regulations limiting or eliminating coal power production. However, since there are still many countries relying on coal power a reduction in FA availability may only be apparent in the medium to long term. The activator in turn, is a caustic chemical and may be a concern for worker health and safety. Governments will most likely impose strict regulations controlling the use of this chemical when constructing with AAC concrete especially on site. This will however not directly restrict access to the raw materials for AAC production but only limit the use of AAC to those people or companies who are able to comply with the safety regulations imposed. These minor possible governmental restrictions resulted in a score of 4 for AAC with all rebar types except for SS, where export restrictions for unprocessed nickel ore in major producing countries are already in effect (score 2) (*314, 315*). The main competition for the raw materials of AAC comes from their use in the production of blended cements (*278*). Despite the necessity to develop cements with lower CO_2 emissions it is unlikely, that the demand for blended cement will decrease in the medium term. However, if it can be demonstrated that AAC concretes have the same long-term performance properties as blended cement concretes a shift in demand may occur (meaning that raw materials will be available for AAC. It is not likely that AAC demand will surpass the demand for blended cement). As these developments are uncertain but there exist no other competing industries for the raw materials required a value of 3 was assigned to the AAC concrete with CS, GFRP and CFRP rebar for this attribute. SS rebar has a lower score (i.e. 1), as the construction industry is only responsible for around 12% of global SS demand and a strong demand increase for nickel and also molybdenum is expected from the rapidly growing renewable energy and electro mobility sectors (*314, 317*). The global production volumes of AAC are currently still miniscule compared to those of OPC. A huge increase in production would therefore be required if this cement types was to be used as a major construction material. Furthermore, a significant increase in the production volumes of the activator would require new production facilities and may even require a scale-up of the current production processes. As this is most likely the limiting factor for increasing production a value of 2 was assigned for AAC with all rebar types.

For CSA concrete the high amount of aluminate mineral (mainly bauxite) presents not only an economic issue, but also influences the overall effect of government regulations, competition and production increase. The production of aluminum alloys for the use in transportation, construction, aerospace and beverage containers is the main competition for bauxite. All these markets are predicted to grow to varying degrees. As around 95% of global bauxite production is converted to metallurgical products the growth of these industries will definitely limit the availability of bauxite for the use in cement (*318*). Thus, due to the high expected demand increase from these industries and the already extensive pressure on bauxite supply the lowest value was assigned to Competition from Competing Industries for all CSA concretes. Concerning government regulations, the relatively high concentration of bauxite reserves in China may present an issue in the longer term. It is possible that China will restrict bauxite exports to ensure enough supply to cover the growing demand of their domestic industries. Consequently, it may be possible, that governments from importing countries require the available raw material to be used in the production of high value aluminum products and not for the production of an alternative cement. As there is some uncertainty surrounding this potential restriction value of 3 was assigned for all CSA concretes. The same value was assigned for Ease of Production Increase since global bauxite production is currently near full capacity and an increase in production volumes by multiple factors would require new mines and processing facilities to be built requiring large, long term investments but no new technological developments.

Concerning recycling, there is a large potential to increase the recycling rates and improve the processes for all concretes in the future. Despite the fact, that current recycling rates for concrete are very low, the aggregate used for concrete production could be almost fully recycled. Various studies have furthermore shown that the use of recycled aggregate in concrete can lead to faster setting times and increased compressive strength compared to natural aggregate (*389*). The full recycling of concrete aggregates is expected to increase significantly around the world with possible local shortages driving prices for natural aggregates in certain regions. The main problem to date is the recycling of the fine fraction recovered from demolished concrete. This fraction contains hardened cement, sand and light contaminants such as wood, plastics, and foams. In order to reuse the hardened cement as a limestone substitute in a cement kiln separation of the cement from sand and other contaminants is required. One process that is currently in development involves the use of Laser induced breakdown spectroscopy (LIBS) to perform real-time analysis of the material being crushed enabling efficient and effective separation according to the chemical composition of the different components (*390*, *391*). The obtained recycled cement could be used to replace low quality limestone in a cement kiln. The future recycling potential for concrete is substantial but there exists a limitation on the possibility to replace virgin material. For pure BC concrete a value of 4 was seen as realistic. Since CSA cement has the same hydration products as BC, it should be possible to recycle the two concretes in the same way, using the same facilities. AAC concrete is also recyclable using similar processes to those used for concrete from blended cements. An essential difference is that there may still be unreacted activator present in the AAC concrete. The main issue is that currently not much data exists on the use of recycled AAC concrete as aggregate for the production of new concrete with BCs. A concern is that the activator could cause unwanted alkali aggregate reaction in the new concrete. This however requires aggregate that is susceptible to alkali aggregate reaction in the first place and should be avoidable. Furthermore, it is also possible that the activator solution reacts with GBFS or FA in BC to form a more rapidly setting and dense concrete. In consequence, the future recycling potential for AAC concrete is seen as very similar to that of concrete from BC or CSA. However, further research on the effects of including crushed products from AAC in BC concrete is needed before it can be widely applied. Combining the values for the pure concretes with those for the individual rebar types resulted in the final scores. Steel and stainless steel rebar are fully recyclable and in the future the recycling rate is expected to increase for both rebar types (score 4). GFRP and CFRP rebar can currently only be ground into fine flakes and used as filler material, thus meaning downcycling. Experts assume that this will not change in the near future (score 3) (*367, 368*).

5.3.5 Improving the Sustainability of the Analyzed Concretes

The previous results describe the overall performance of the analyzed concretes in the present. The cement technology roadmap developed by the International Energy Agency and the Cement Sustainability Initiative includes various approaches to improve the sustainability of global concrete production and use (*276*). In this section the presented ranking framework is used to focus on the effect three specific developments which address the main weaknesses of the evaluated concretes may have in the long-term. As can be seen in Table 5.12 the analyzed concretes achieve very low scores for Recycling Approach, Growth of Competing Industries, Ease of Production Increase, as well as Performance Uncertainty. To improve these scores recycling rates need to be increased globally, substitutes need to be found for the critical raw materials, and the risk involved with the use of alternative materials needs to be reduced.

As described in the previous section technological developments enabling more efficient and complete recycling of concrete already mostly exist or are in the later stage of development. Therefore, the main factors limiting the widespread recycling of concrete are related to organizational complexities (development of an efficient value chain involving all stakeholders from demolition to recycling and construction) and lacking support and incentives provided through government policies (*392*). Thus, to fully realize the large recycling potential for concrete, construction regulations need to be adapted to reflect the increasing pressure for sustainable practices in society. An example is reducing or eliminating the requirement for higher safety margins concerning the strength of concrete if recycled aggregate is used. Further incentives supporting the recycling of concrete such as landfilling taxes and investments into suitable recycling infrastructure will further increase recycling rates for all types of concrete (*393*). This would increase the Recycling Approach scores for all analyzed concretes to the same value as those for Development of Recycling Infrastructure (Green bar in Figure 5.1).

For the substitution of critical raw materials, the use of calcined clays presents a very promising option. These clays can be used to replace GBFS in BC, FA as the solid precursor in AAC and, as certain types of clay (ex. kaolinitic clays) contain a higher amount of alumina, they may also be able to replace bauxite as an alumina source for the production of CSA cement (*233, 394*). Although the investigations into the use of clays instead of GBFS are still ongoing most experts agree that this substitution should be achievable without any detrimental effect on mechanical performance or durability of the concrete (*187*, *395*). For the substitution of FA in AAC concrete and bauxite in CSA cements existing results are also promising, although additional research is still required (*396, 397*). Reserves of these clays can be considered unlimited and are globally widespread effectively increasing the Geographical Distribution and Potential for Government Regulation scores for all AAC and CSA concretes to the level of those of the corresponding BC concretes. Furthermore, this large availability will eliminate the supply issues currently affecting GBFS, FA and bauxite, consequently increasing the Growth of Competing Industries score for all cement types (5 for CS, 1 for SS, 3 for GFRP and CFRP). Finally, production increases for BC will be easier to achieve, as many concrete producers currently have overcapacities. If new plants would be required, the technology of cement production is very well established and would only require investments into proven existing technologies (score 4 for CS, 3 for SS, GFRP and CFRP). For AAC this score would not change, as increasing production of the activator still presents a major barrier. The same would be true for CSA cement, as additional technological developments are still required before it can be produced from clays on an industrial scale. As a consequence of these improvements, the substitution of these materials with calcined clays (or other widely available, waste materials) would increase the Future Availability scores of all cements leading to the final scores shown as blue bars in Figure 5.1.

Finally, as the scores of the original ranking show, alternative rebar and cement types may present a sustainable alternative to BC and CS especially in regions where there are local deficiencies of necessary raw materials or if structures are built in highly corrosive environments. To encourage more widespread adoption of these materials in the industry, codes and standards will need to be established to reduce the associated risks (*194*). This process could be greatly expedited through government action such as the funding of pilot projects and research programs to establish empirical data. Furthermore, construction codes need to be adapted more frequently to reflect such new research results. The consequence would be an increase of the Performance Uncertainty score of all concretes to the maximum value which would lead to the final scores depicted as yellow bars in Figure 5.1.

The mentioned developments will also have further effects, such as decreasing the costs and EIs of production for the various concretes. However, a scenario-based calculation of the potential future values for these attributes was beyond the scope of this evaluation.

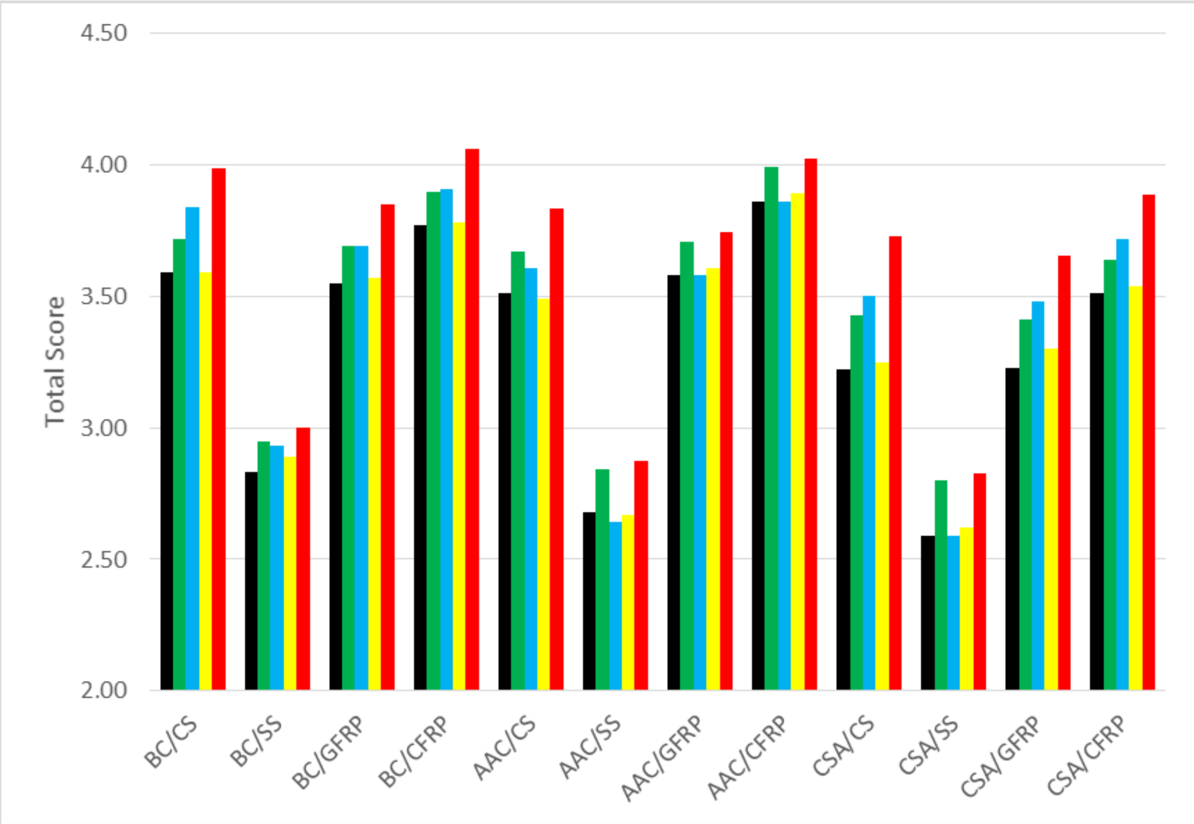

Figure 5.1: Effect of material development and policy measures on total scores of analyzed cements (Black: Original Score, Green: Increasing recycling rates to full potential through technological development, incentives for using recycled concrete and adaption of construction standards, Blue: Substituting GBFS, FA and bauxite with calcined clays, Yellow: Eliminating uncertainty through active support of pilot projects and updating of standards according to new experimental findings, Red: Combination of all improvements

5.3.6 Summary

The results of this section provide a high-level overview of the advantages and disadvantages associated with the use of different cement and rebar types for sustainable construction in the marine environment. While the overall best scores are achieved by BC and AAC concrete, CSA concrete scored slightly lower mainly due to the increased demand for bauxite as a raw material. CFRP rebar showed a marginally better performance than CS and GFRP rebar which are significantly better than SS. The main weaknesses of all evaluated concretes are the currently still very low recycling rates and supply issues of specific raw materials required for clinker production. An essential step to address these issues will be an accelerated adaption of existing construction codes and standards to recent empirical findings in order to encourage recycling and the use of alternative materials.

5.4 Timber

5.4.1 Goal of Ranking

In this section, the goal of the following ranking is to compare the long-term performance of different timbers for the sustainable use as structural components in marine construction. The performance of all timbers is assessed without the consideration of any additional protection methods.

5.4.2 Definition of Functional Unit

The FU used for this analysis was the amount of material required to produce a 150 mm thick plate with an area large enough to withstand a compressive load of 1225 kN (thus a material's compressive strength determines the amount of material required).

5.4.3 Composition and Mechanical Properties

As previously mentioned, one specific species was chosen to represent each timber category to enable exact calculations concerning price and EI. The mechanical properties used for all timber calculations were taken in the dry condition defined as a moisture content of 12% (Table 5.15).

Table 5.15: Mechanical properties of analyzed timbers (based on data from 398)

Timber Category	Species	Compressive Strength [MPa]
Softwood	European Larch (*Larix decidua*)	54
Hardwood Non-Tropical	Black Locust (*Robinia pseudoacacia*)	70.2
Hardwood Tropical	Ekki (*Lophira Alata*)	98.1

5.4.4 Timber Ranking Results

Table 5.16 displays the scores achieved by the evaluated timbers for each attribute as well as the individual category scores and the final score. The reasoning behind the individual scores will be discussed in detail in the following subsections.

Table 5.16: Attribute and category scores of ranked materials

Category	Attribute	Softwood	Non-Tropical Hardwood	Tropical Hardwood
Durability	Corrosion Resistance	5	5	5
	Resistance to Biological Degradation	1	2	3
	Fatigue Resistance	4	4	4
	Resistance to Stress Corrosion Cracking	3	3	4
	UV Resistance	4	4	4
	Moisture Resistance	1	2	4
	Category Score	2.69	3.15	4.00
Economics & Costs	Material Costs	5	1	3
	Ease of Manufacture	3	2	2
	Maintenance Cost - Vulnerability	3	3	3
	Maintenance Cost - Repairability	4	4	4
	Reaction to Fire	2	2	2
	Resistance to Fire	3	3	3
	Performance Uncertainty	5	5	5
	Projected Price Developments	1	1	1
	Category Score	3.44	2.63	3.00
Sustainability	Raw Material Renewability	5	5	5
	Recycling Approach	5	5	5
	Impact of Production on Human Health	3	5	1
	Impact of Production on Ecosystems	3	5	1
	Impact of Production on Resources	1	5	3
	Category Score	3.55	5.00	3.18
Future Availability	Short-Term Availability	5	5	5
	Long-Term Availability	5	5	5
	Geographical Distribution of Reserves	5	5	5
	Potential for Restrictive Government Regulation	5	5	1
	Development of Recycling Infrastructure	5	5	5
	Projected Growth of Competing Industries	4	4	4
	Ease of Production Increase	2	2	1
	Category Score	4.69	4.69	4.13
	Total Score	**3.75**	**4.12**	**3.72**
	Rank	**2**	**1**	**3**

5.4.4.1 Durability

While all timbers are inherently corrosion resistant (score 5), they suffer from a low biological and moisture resistance due to their biodegradable nature. For instance, softwood is attacked and degraded completely in a short period of time by wood boring organisms and also fungi in the splash zone. They are seen as nondurable timber species and usually deteriorate in under a year (score 1). Non-tropical hardwoods have a slightly higher resistance to marine borers than softwoods but are also degraded completely over less than 20 years, especially under conditions of heavy attack (score 2). An exception are the tropical hardwoods, where a few species have a strong resistance to marine organisms and can achieve lifetimes well over 25 years (score 3) (*399–403*).

The scores are similar for moisture resistance. In general, an increase in moisture content of timber causes the mechanical properties of the material to decrease. For softwood this decrease can reach up to 50% compared to the dry timber. While this process is reversible, repeated shrinking and swelling can lead to cracking of the timber. Furthermore, a high moisture level strongly increases the potential for fungi attack which quickly degrades the material (score 1) (*404*). While the mechanical reductions are slightly smaller for non-tropical hardwoods the overall concerns are the same as for the softwoods (score 2). The limited moisture absorption tendency and higher biological resistance of tropical hardwood leads to a significantly higher moisture resistance (score 4).

These scores are reflected in the stress corrosion cracking scores of the timbers. Extensive exposure to repeated impact forces from waves can cause timber to crack. These cracks allow organisms such as fungi to settle on the inside of the wood increasing the degradation rate substantially (score 3 for softwood and non-tropical hardwood, score 4 for tropical hardwood).

Fatigue and UV resistance are both rated well for all timbers (score 4). While the surface of timber components can be slightly degraded through UV radiation, this is mainly an aesthetic concern. As the effect is limited to the immediate surface layer, mechanical properties are only marginally altered, as long as no wood-destructive fungi manage to establish due to surface degradation.

5.4.4.2 Economics and Costs

Softwoods are by far the cheapest type of timber. Tropical and non-tropical hardwoods are more than twice as expensive per FU (Table 5.17).

Concerning Ease of Manufacture, timber can easily be cut and formed into different shapes but requires a factory to fabricate the original component from a log. The big drawback of pure timber is that the size and shape of different components is limited by the size of the log from which the component is produced. Onsite joining and reshaping of components can however be done easily with simple equipment (score 3 for softwoods). The increased toughness of hardwood timber requires more expensive equipment, which also needs to be replaced more often due to wear, thus slightly reducing the score for both non-tropical and tropical hardwood (score 2) (*405*).

Timber is rather susceptible to damage compared to materials such as metals or concrete. However, due to its relatively high ductility it can resist impact loads very well and depending on the crack direction damage can remain local leading to an average Vulnerability score (i.e. 3) for all timbers. If damage does occur, timber is very versatile when it comes to repairs. Depending on the type of damage and location of components all options from full replacement to onsite repair can be considered (Repairability score 4 for all timbers).

While timber products such as wood-based panels are classified as class D materials according to EN 13501-1 (*252*) making them the low scoring materials concerning Reaction to Fire (score 2), they show a better Resistance to Fire than certain other materials. For instance, while CS loses mechanical strength rapidly at elevated temperature, timber burns at a very predictable rate. Char formation on the surface exposed to fire protects the internal material from damage for a certain time and decreases the burn rate. As timber has a low thermal conductivity the internal part of a component not exposed to flame remains cool and retains its mechanical strength. Since the burn rate of timber can be calculated rather precisely, components can be designed with an appropriate thickness to achieve a desired lifetime in specified fire conditions (score 3) (*406–409*).

As many types of softwoods as well as hardwoods have been used in the marine environment for centuries, be it for the construction of ships, pier like structures or defense works, Performance Uncertainty is very low (score 5). The performance characteristics are well known, and timber types are classified according to their strength and durability. Specific codes exist on how to construct with timber of a given class (*399, 410*).

An issue with increasing use of timber in construction is the associated expected increase in price. Demand for timber is expected to increase due to economic recovery in industrial nations, sustained growth from developing nations and increased generation of energy from biomass, along with supply constraints. These stem from the fact that easily harvested resources have been exploited and increasing environmental constraints will increase the cost of exploitation in the future. Furthermore, due to increasingly far reaching environmental protection policies, more forests may be excluded from timber production. Since afforestation is not seen as a viable approach to significantly increase the exploitable reserves of timber, demand growth will have to be met from existing resources, which will become increasingly remote and thus more expensive to access and harvest. Therefore, prices for softwoods and non-tropical hardwoods could increase by over 50% in the next five to ten years. These points are also valid for the tropical hardwoods. However, since the harvest of these types of timber is largely associated with illegal logging and global forest loss, export restrictions and environmental policies have a larger restraining effect on supply than for the other timber types. Furthermore, potential supply is being greatly reduced by conversion of tropical forests to agricultural land. Therefore, it is expected that price increases for tropical hardwoods, especially if sourced from sustainably managed forests, will exceed those of softwoods and non-tropical hardwoods (score 1 for all timbers) (*411*, *412*).

5.4.4.3 Sustainability and Environmental Impact

As completely renewable materials, all timbers achieve the maximum renewability and recycling approach score (i.e. 5). Since timber is a renewable material, recycling as such does not really exist. Timber components can be reused a number of times as long as their mechanical strength is sufficient for the application. At the end of their lifetime they can be ground up and compressed with an epoxy resin to produce fiberboard or they can be burnt to recover energy in the form of heat. Due to the renewable nature, the maximum was assigned even if substitution of virgin material (as for instance with CS recycling) is not possible.

Concerning EI of production, the soft- and non-tropical hardwood timbers have the lowest and second lowest total impacts, while tropical hardwood has the highest overall impact per FU (Table 5.17). As only the three timbers are compared in this section the scores of the EI attributes are far lower than if any other material would be included. All timbers have a far lower impact per FU on resources compared to other materials evaluated in this thesis, as they are renewable materials and require comparably small amounts of petroleum and electricity for logging and processing. However, the EI on ecosystems is higher than for some other materials, especially for tropical hardwood, which has an almost 10 times higher EI on ecosystems per FU than CS (although the total EI per FU is very similar). This high EI on ecosystems is caused in part by the assumption that the entire forest area required for timber production cannot be used for other economic, social or environmental functions. The transformations of large areas of natural forest to managed forests and industrial facilities (roads, processing facilities etc.) thus significantly reduces biodiversity leading to a high impact on the local ecosystems (this effect is particularly large for tropical forests) (*413, 414*). While there will definitely be a decrease in biodiversity when transitioning from a natural to a managed forest, it will most likely not be quite as extreme as it is modeled in this calculation. Finally, the production of softwood and non-tropical hardwood timber leads to very low impacts on human health, while tropical hardwood production has a significantly higher impact on human health. The reason for this is that the tops and branches of the felled trees are usually burned, producing large amounts of smoke which is hazardous to human health (*414*).

Table 5.17: Mass, price and EI per FU of analyzed timbers (based on data from 296 and the ecoinvent 3.3 database)

- Material	kg/FU	Price [$/FU]	Environmental Impact [mPt/FU]			
			Human Health	Ecosystems	Resources	Total
Softwood	1.81	1.78	17.3	277.2	12.1	306.6
Hardwood Non-Tropical	1.86	4.27	13.4	199.0	8.6	221.1
Hardwood Tropical	1.84	4.21	140.4	810.2	11.0	961.6

5.4.4.4 Future Availability

The future availability for all timber types can generally be considered unlimited, as they are renewable resources. No data estimates on resources and reserves of the specific timber types could be found in order to calculate the reserve/resource to production ratios as with the other materials. However, a report by the FAO shows that global temperate forest area has increased over the past 25 years (score 5 for softwoods and non-tropical hardwoods) (*415*). Globally, forest area has however decreased, mainly due to destruction of tropical forests. Dividing the globally available tropical forest area by the average yearly deforestation rate resulted in a value of over 250 years (*416*). Naturally, this does not mean that tropical hardwood is readily available, as logging is associated with huge environmental impacts and deforestation is a global problem that must be addressed immediately. Nevertheless, in the boundaries of this ranking this is equivalent with a value of 5 for short and long-term availability of tropical hardwoods.

Again, for the geographical concertation no data could be found to directly calculate the correct value for the different timber types. However, for none of the timbers resource concertation presents an issue. Production of softwood lumber exists in over 100 countries globally, which accounts for about half the world's countries (*411*). For the hardwoods (non-tropical and tropical) country specific production volumes were available, allowing the calculation of an Herfindahl-Hirschman-Index (HHI) of concentration for the production of non-tropical and tropical timber products (*417*). The HHI of production has a value below 1500 which corresponds to a score of 5 for both timber types.

Aside from the tropical hardwoods, government regulation is not considered as a major threat to global timber supply. In general, the use of wood in construction is starting to increase again as many governments focus strongly on issues of sustainability. Sustainable building policies in many countries are expected to even drive demand for timber in construction (*412*). While some environmental policies may also limit the harvest of lumber from certain forests, thus decreasing supply, it is expected that most governments will provide incentives for the use of timber (score 5 for softwood and non-tropical hardwood). Tropical hardwoods however are the main type of timber that is cut down illegally, leading to the immense shrinkage of global rainforest area of around 7 million hectares per year (*418*). Supply of tropical hardwood timber logging is strictly controlled and strongly limited by law already today (score 1).

As mentioned, the renewable nature of timber and the possibility of reusing it in various ways gives these materials the highest possible recycling potential scores (i.e. 5). In the future, with increasing use of timber as a construction material, the market and uses for used timber will grow and therefore further increase the potential use options of a given piece of timber.

Competition from industries beside the construction industry is small for timber products. The construction industry is currently the main consumer of softwood and non-tropical hardwood timber products, responsible for around 60-70% of total demand, and is also seen as the main driver of demand in the future. Other industries include paper and packaging, as well as furniture production. The same is true for tropical hardwood timber, except that it is mostly too valuable to be considered for the use in the paper and packaging industry. Structural components are more common for smaller scale construction in the marine environment such as piers, while joinery is the main use of tropical timber in land-based construction. For furniture production timber only represents a small portion of raw materials and tropical hardwoods only a small percentage of all timbers used. It is expected that the use of timber in construction will increase in the future due to green building policies in developed nations and growing demand in developing countries. A major new industry which will also drive demand for timber resources is the use of wood biomass for energy production. However, the main source for biomass are not full-size logs, but rather sawmill residues, which traditionally have been used as feedstock in the paper and packaging industry. Therefore, while it is assumed that timber supply will have difficulty keeping up with growing demand, this demand is expected mainly from uses in construction (score 4 for all timbers) (*292, 411, 412*).

Increasing the global supply of timber from all sources presents the major challenge associated with globally increasing usage of timber in construction. The supply of timber is seen as relatively fixed as there are no new reserves to be found globally. Traditional reserves of timber take decades to be replaced (10-35 years for softwoods, 40-100 years for hardwoods). New supply can only be created by establishing new plantations which require a similar amount of time before the timber can be harvested for the use in construction. These plantations furthermore require high quality soil and thus compete with agriculture for any viable and available locations (*412, 419*). Due to this long timeframe for the development of new resources a quick reaction on the supply side to increasing demand is impossible. The establishment of new plantations with potentially modified timber species can, in the scope of this framework, be seen as being similar to the development of new production technology (score 2 for all timbers for Ease of Production Increase).

5.4.5 Summary

This section compares the performance of softwood, non-tropical hardwood and hardwood timbers according to their potential for use in sustainable marine construction.

Concerning Durability, the particular moisture resistance as well as the resistance towards many wood boring organisms of tropical hard-wood lead to the highest durability score for this timber type. This is followed by non-tropical hardwoods, which are also inherently corrosion resistant but are more susceptible to moisture and biological attack. The timber with the lowest Durability score is softwood, which has a very low moisture and biological resistance (which is exacerbated when mechanical forces cause cracking of the surface) making it a rather unsuitable material for marine construction without the application of additional protection measures such coatings or physical and chemical treatments. In the economics and costs category softwoods, also being the cheapest timbers, achieve the highest score. They exhibit an average performance concerning manufacturability, overall maintenance costs and even fire safety. Non-tropical and tropical hardwoods are somewhat more expensive and, due to their increased density, more difficult to manufacture. This slightly decreases their score compared to the softwoods. The Sustainability and Environmental impact category is where the timbers perform very well. The only large source of impact is related to ecosystem degradation associated with the transformation of large areas of natural forest (especially for the tropical hardwoods). Finally, Future Availability is another strong point of the timbers, with the only weaknesses being the difficulty to greatly improve global production levels and government regulations limiting the use of tropical hardwoods in light of the globally occurring degradation of tropical forest area.

These results show that overall different types of timber present themselves as exceedingly promising materials for sustainable construction in the long-term future. Nevertheless, in order to achieve more widespread application the main weaknesses such as a low moisture and biological resistance and the long time frames required for production increases need to be further addressed through for instance the development of environmentally friendly coatings, and the development of long-term plans for managed forests factoring in the expected rise in demand for large scale timber components.

5.5 Evaluation and Comparison of all Materials

In the previous subsections each material category was analyzed by itself, the scores for the respective materials were discussed in detail and various improvement options were presented and prioritized on a high level for each category. This subchapter now compares all materials included in this thesis to demonstrate the full potential of the developed framework. Next to the materials covered in the previous sections, a new type of thermoset matrix material, phenolic, was added to the category of FRPCs. The attribute scores of these phenolic FRPCs are almost exactly the same as those of the corresponding epoxy composites, with the exception of Resistance to Fire which is rated as 4 instead of 3. Therefore, the individual scores of these material is not discussed specifically in this chapter. The ranking results in this section do however briefly summarize the performance of each material category, while the final evaluation of improvement approaches focuses only on the 15 highest ranked materials.

5.5.1 Goal of Ranking

The goal of the complete ranking presented in this section is to identify those structural construction materials that are most suitable for the sustainable use in marine construction in the long-term future. The performance of the individual materials is ranked for the isolated material without the consideration of any additional protection methods such as coatings.

5.5.2 Definition of Functional Unit

In order to compare different materials performance levels when used as structural components a measure of compressive strength was chosen as the FU. It was calculated for each material how many 150 mm cubes would be required to carry a mass of 1225 kN (1 cube = 50 MPa compressive strength). This measure is based on the commonly used standard for concrete compressive strength testing.

5.5.3 Composition and Mechanical Properties

The composition and mechanical properties are presented in the individual sections covering the specific material categories, as well as in Appendix A.6.

5.5.4 Complete Ranking Results

The discussion of each individual material is presented in the previous sections covering the respective material categories. The values of the complete ranking are shown in Appendix A.1-A.5. As mentioned, this section focuses mainly on the 15 highest ranked materials. Since a high importance was given to Future Availability in the weighting process, these materials all have relatively high scores in this category. The scores for the 15 top ranked materials are shown in Tables 5.18-5.22.

Table 5.18: Category and total scores for 15 highest ranked materials

Material – Category	Material – Subcategory		Durability Score	Economics Score	Sustain-ability Score	Future Availability Score	Total Score	Rank
Metals	Carbon Steels		3.00	4.25	2.45	4.44	3.56	**15**
Concrete	Blended Cement	Steel	4.38	4.31	3.09	4.31	4.03	**2**
		GFRP	4.54	3.94	3.18	3.69	3.81	**8**
		CFRP	4.92	4.19	3.18	3.69	3.93	**3**
	Alkali Activated Cement	Steel	4.38	4.44	2.82	3.81	3.79	**9**
		GFRP	4.54	4.31	3.18	3.63	3.83	**7**
		CFRP	4.92	4.31	3.18	3.63	3.92	**6**
	CSA Cement	GFRP	4.54	3.75	3.18	3.13	3.57	**14**
		CFRP	4.92	3.94	3.18	3.13	3.69	**10**
Composite	Carbon Fiber	Epoxy	4.54	3.44	2.73	3.75	3.65	**12**
		Phenolic	4.54	3.38	2.91	3.75	3.69	**11**
		Vinyl Ester	4.08	3.13	3.27	3.75	3.63	**13**
Timber	Softwood		2.69	3.44	4.27	4.69	3.93	**4**
	Hardwood Non-Tropical		3.15	3.19	4.45	4.69	4.06	**1**
	Hardwood Tropical		4.00	3.19	3.91	4.13	3.92	**5**

Table 5.19: Durability scores for 15 highest ranked materials

Category	Subcategory		Corrosion Resistance	Resistance to Degradation by Marine Organisms	Fatigue Resistance	Resistance to Stress Corrosion Cracking	UV Resistance	Moisture Resistance
Metals	Carbon Steels		1	3	3	2	5	5
Concrete	Blended Cement	Steel	4	5	4	3	5	5
		GFRP	5	5	4	4	5	4
		CFRP	5	5	4	5	5	5
	Alkali Activated Cement	Steel	4	5	4	3	5	5
		GFRP	5	5	4	4	5	4
		CFRP	5	5	4	5	5	5
	CSA Cement	GFRP	5	5	4	4	5	4
		CFRP	5	5	4	5	5	5
Composite	Carbon Fiber	Epoxy	5	5	4	5	3	4
		Phenolic	5	5	4	5	3	4
		Vinyl Ester	5	5	4	5	3	2
Timber	Softwood		5	1	4	3	4	1
	Hardwood Non-Tropical		5	2	4	3	4	2
	Hardwood Tropical		5	3	4	4	4	4

Table 5.20: Economic scores for 15 highest ranked materials

Category	Subcategory		Material Costs	Ease of Manufacture	Vulnerability	Repairability	Reaction to Fire	Resistance to Fire	Performance Uncertanty	Projected Price Developments
Metals	Carbon Steels		5	4	4	5	5	2	5	3
Concrete	Blended Cement	Steel	5	5	4	4	5	4	4	3
		GFRP	4	4	4	4	5	4	2	3
		CFRP	5	4	4	4	5	4	3	3
	Alkali Activated Cement	Steel	5	5	4	4	5	5	2	5
		GFRP	5	4	4	4	5	5	1	5
		CFRP	5	4	4	4	5	5	1	5
	CSA Cement	GFRP	4	3	4	4	5	3	1	4
		CFRP	5	3	4	4	5	3	1	4
Composite	Carbon Fiber	Epoxy	4	4	3	4	3	3	3	3
		Phenolic	3	4	3	4	4	3	3	3
		Vinyl Ester	3	4	3	4	3	3	1	3
Timber	Softwood		5	3	3	4	2	3	5	1
	Hardwood Non-Tropical		4	2	3	4	2	3	5	1
	Hardwood Tropical		4	2	3	4	2	3	5	1

Table 5.21: Sustainability & Environmental Impact scores for 15 highest ranked materials

Category	Subcategory		Raw Material Renewability	Recycling Approach	EI of Production on Human Health	EI of Production on Ecosystems	EI of Production on Resources
Metals	Carbon Steels		1	5	2	2	1
Concrete	Blended Cement	Steel	1	2	4	5	4
		GFRP	1	1	5	5	5
		CFRP	1	1	5	5	5
	Alkali Activated Cement	Steel	1	1	4	5	4
		GFRP	1	1	5	5	5
		CFRP	1	1	5	5	5
	CSA Cement	GFRP	1	1	5	5	5
		CFRP	1	1	5	5	5
Composite	Carbon Fiber	Epoxy	1	2	4	4	3
		Phenolic	1	2	4	4	4
		Vinyl Ester	1	2	5	5	4
Timber	Softwood		5	5	5	1	5
	Hardwood Non-Tropical		5	5	5	2	5
	Hardwood Tropical		5	5	3	1	5

Table 5.22: Future Availability scores for 15 highest ranked materials

Category	Subcategory		Reserves/ Production Ratio	Resource/ Production Ratio	Geographical Distribution of Resources	Potential for Re-strictive Govern-ment Regulation	Development of Re-cycling Infra-struc-ture	Projected Growth of Competing Indus-tries	Ease of Production Increase
Metals	Carbon Steels		2	5	4	5	5	5	5
Concrete	Blended Cement	Steel	3	5	4	5	4	5	4
		GFRP	3	4	5	4	3	3	3
		CFRP	3	4	5	4	3	3	3
	Alkali Activated Cement	Steel	3	5	4	4	4	3	2
		GFRP	3	4	5	4	3	3	2
		CFRP	3	4	5	4	3	3	2
	CSA Cement	GFRP	3	4	4	3	3	1	3
		CFRP	3	4	4	3	3	1	3
Composite	Carbon Fiber	Epoxy	3	4	5	4	4	2	3
		Phenolic	3	4	5	4	4	2	3
		Vinyl Ester	3	4	5	4	4	2	3
Timber	Softwood		5	5	5	5	5	4	2
	Hardwood Non-Tropical		5	5	5	5	5	4	2
	Hardwood Tropical		5	5	5	1	5	4	1

5.5.4.1 Metals

For the metals there are differences mainly between carbon steel and the other alloy types. In general, the alloys have a good to excellent Durability with the only issue being MIC (for stainless steel & aluminum alloys) and a missing fatigue limit (for aluminum and nickel-copper alloys). Carbon steel on the other hand has a very low Corrosion Resistance and definitely needs to be protected if it is to be used in the marine environment. Concerning Economics and Costs, carbon steel performs better than the other metals, as it is relatively cheap, easily manufacturable and easy to repair. Furthermore, it has been used extensively in marine construction in the past. Aluminum alloys perform similarly well in this category, although they are slightly more vulnerable as they have a lower stiffness. The other alloys which have a higher Durability are significantly more expensive due their higher content of specialized alloying elements and are thus also more complicated to manufacture and repair. Finally, except for the carbon steels all metal prices are expected to increase in the future. Concerning Sustainability & EI, the true strength of metals is their recyclability. All ranked metals have recycling rates of over 60% when used in construction. Recycling is very important for metals, as the EI of their production is very high. Carbon steel is the only material with an impact rating higher than 1. This is mainly due to the impacts associated with the mining of the individual raw materials and the large amount of fossil energy required for processing. The Future Availability scores for carbon steel again differ significantly from the other metals. The raw material resources of all raw materials required for the production of carbon steel (Fe, C, Cu) are large, geographically well distributed and no significant competition for these resources from multiple industries is expected in the future. For the other metals Future Availability is severely limited by highly concentrated and limited resources (for those containing Cr, V & Mo) or strong expected demand growth by competing industries in the coming decades (For those containing Ni & V). Thus, with the high weight given to Future Availability in the overall ranking, carbon steel is the only metal to rank amongst the top 15 materials in this study.

5.5.4.2 Reinforced Concrete

The concretes are amongst the highest-ranking materials. The only materials that are not amongst the top 15 are those with stainless steel rebar (due to the high cost, impact of production and low availability of stainless steel) as well as the calcium sulfoaluminate (CSA) cement with steel rebar. Durability of the different concretes is determined mainly by the type of reinforcement used as the concrete itself does not corrode, is not attacked by marine organisms and can neither be strongly damaged by UV or moisture. Here steel presents the worst option as it corrodes if chlorides present in seawater penetrate far enough into the concrete. However, proper mix design and sufficient concrete cover can also ensure long lifetimes for this rebar type. GFRP rebar also have a slight weakness. The glass fibers can be degraded by the alkaline environment within the concrete if the polymer matrix is damaged and also slowly degrade if sufficient moisture is able to penetrate into the concrete. CFRP rebar present the best option as they are not affected by any of these mechanisms. Despite the high Durability scores, it needs to be mentioned that to achieve a high durability the proper concrete mix design is of paramount importance. All concretes are amongst the cheaper materials for achieving a given compressive strength. The prices for GFRP and stainless steel rebar are slightly higher than those for steel or CFRP rebar. For the CFRP this is mainly due to the fact that less rebar is required to achieve the desired increase in tensile strength than for the other rebar types (*291*). Concrete components have a high manufacturability, as they can be cast on-site and have little limits concerning their shape and size. As GFRP and CFRP rebar needs to be prefabricated into the desired shapes (steel and stainless steel can be welded on-site) they have a slightly lower manufacturing rating. All concretes have a low Vulnerability and high Reparability. Furthermore, they are inflammable and have a high fire resistance. The exception is CSA concrete which, with its higher ettringite content, loses strength more rapidly in elevated temperatures due to the evaporation of bound water molecules (*420*). This leads to an increase in porosity of the CSA concrete at elevated temperatures and a significant reduction in strength (*386*). The main weakness of the alternative cements (alkali activated, CSA) and rebar types (GFRP, CFRP) is that, since these are relatively new materials, few codes and standards exist for their use in construction. Concerning Sustainability, the EI of production for the different concretes is amongst the lowest for the evaluated materials and given FU. Nevertheless, it is important to point out, that due to the sheer amount of cement being manufactured globally, the industry is responsible for around 8 % of global CO_2 emissions and significant efforts are required to reduce these impacts (*233*). Recycling rates for concrete are very low globally and the majority of demolition waste is dumped in landfills (esp. outside of Europe). This is expected to change in the coming years, as more and more concrete waste is downcycled for the use as aggregate in road construction or even new concrete. Full recycling will however not become possible in the future as it is practically impossible to fully separate and reuse the cement after hydration and binding to the aggregate (*421*). Aside from the chromium required for the production of stainless steel rebar, the raw materials for the production of the different reinforced concretes are readily available and globally widespread. Otherwise, only bauxite required for the production of CSA concrete presents a major issue, as it is mainly used for the production of aluminum and aluminum alloys. The demand for aluminum is expected to increase significantly in the coming decades, which may lead to potential supply constraints for the use of bauxite in CSA concrete. Thus, the blended cement and alkali activated cement concretes rank slightly higher than the corresponding CSA concretes. Steel rebar ranking slightly lower than GFRP and CFRP rebar concerning Durability and Sustainability is therefore not amongst the 15 highest ranking materials for the CSA cement.

5.5.4.3 Fiber Reinforced Polymer Composites

For the composites only thermoset matrices reinforced with CF are amongst the top 15 materials. This is mainly due to the high stability and strength of CF which lead to a higher Durability and lower price and EI of production for the defined FU. Concerning Durability, the analyzed composites in general have a lower score than the metals or concretes categories. Firstly, the polymer matrix can be damaged by UV radiation. But more importantly, all polymer matrices absorb a certain amount of moisture, which leads to swelling of the matrix. This can lead to a degradation of the matrix-fiber interfacial bond which reduces the mechanical strength of the component. Thermoset matrices tend to absorb less moisture than thermoplastic matrices with vinylester being the most suitable matrix for seawater application, as it is highly resistant to leaching (*269, 422, 423*). Furthermore, NF and GF degrade over time when exposed to moisture which penetrated into the matrix. This is not the case for CFs leading to the relatively high Durability score for these composites. Economically composite materials are ranked amongst the more expensive materials in this study (only slightly cheaper than the specialized metal alloys). As mentioned, the small amount of CFRP needed for a FU leads to the costs being lower than for the other composite types. Overall, the Manufacturability, Vulnerability and Repairability are similar for all fiber types. Thermoset matrices perform slightly better than thermoplastics for these attributes. As they don't require heat for curing, they can be used to manufacture components on-site by vacuum assisted resin transfer molding or, for lower quality components, hand-lay-up. Furthermore, it is also possible to repair damage (to a certain limit) on-site. Fire reaction and resistance is a weakness of all polymer composite materials, as the polymer matrices degrade at elevated temperatures. A further weakness of the composite materials is their low recycling rate. Currently no technology exists to fully recycle these materials especially with a thermoset matrix as the resin cannot be uncured once hardened. Therefore, downcycling is the only disposal option beside incineration or landfilling. For downcycling, which represents only a small percentage of treated waste, the composite is ground into fine powder and used as filler in concrete or other composites (*367*). For CFRPs this can be slightly compensated by the low EI of production (due to the high strength and thus small amount required for a FU) resulting in an average overall Sustainability score, which is higher than for the other fiber types. Concerning Future Availability, the amount and distribution of resources for the production of all composite materials (Oil, silica sand, basalt rock, and plants) is not an issue and the scores are similar to those for the different concrete types. CFRP however, differ from the other fiber types in two main points. They have a higher recycling potential, but also higher competition from competing industries, mainly aerospace, automotive and wind energy (*372, 373*). For recycling, CFRPs are the only composite material for which a certain amount of full recycling could be possible in the long-term future. Due to their stability they can withstand the aggressive processes (pyrolysis, solvolysis) for removal of the matrix material without being fully degraded. Nevertheless, currently the recycled CFs lose around 50 % of their strength during their recycling process so they cannot replace virgin fibers. However, further research is ongoing to improve this process and retain a larger proportion of the fibers' mechanical strength (*367*). As Recycling Potential has a higher weight than Projected Growth of Competing Industries the CFRPs have the highest Future Availability score of all the composite materials, and also higher than most concrete types.

5.5.4.4 Timbers

The final material category, the timbers, are all ranked amongst the top 5 materials due to their high Sustainability and Future Availability scores, which stem from their Renewability. The Durability score of softwood and non-tropical hardwood is however very low due to a high susceptibility to biological attack and moisture. Tropical hardwood is in general superior in this regard to the other timbers as it has a higher density, and some species even contain natural toxic extractives that have biocidal properties (*410*). All timbers are amongst the cheaper materials in the ranking. Nevertheless, their increased vulnerability to fire and a strong expected increase in timber prices result in an overall mediocre Economics score. As mentioned, the Renewability of timber results in the timbers achieving the highest Sustainability ratings of all analyzed materials. Tropical hardwood however is often cut down illegally leading to the immense shrinkage of global rainforest area of around 7 million hectares per year (*418*). This is reflected in the low ratings for EI of Production on Human Health and Ecosystems giving it the lowest Sustainability rating of the timbers. Supply of tropical hardwood logging is therefore also strictly controlled in most producing countries and imports are limited by governments around the world to sustainably sourced timber. While this is a necessary measure to protect highly endangered tropical forests, it does limit the availability of tropical hardwoods on the market, reducing the score. Furthermore, the supply of timber is seen as relatively fixed. Traditional reserves take from 10 to 100 years to replenish. New supply can only be created by establishing new plantations which require a similar amount of time before the timber can be harvested for the use in construction. These plantations require high quality soil and thus compete with agriculture in suitable locations (*412*). Due to the long timeframe for the development of new resources a quick reaction on the supply side to increasing timber demand is impossible. Nevertheless, in the long-term, the fact that trees of a desired species can be actively planted in any location with suitable climatic conditions, means that the Future Availability is theoretically unlimited for all timber types, making them highly promising construction materials for the future.

5.5.5 Focus Areas for Research and Development

5.5.5.1 Carbon Steel

For carbon steels the main weak points are Corrosion Resistance (weight 3), to a certain extent Fire Resistance (weight 2) and the high EI of Production (weight 2). Multiple approaches are already broadly employed to increase the corrosion resistance of steel such as sacrificial anodes, or various kinds of organic and inorganic coatings. Further research in this area is well warranted, as carbon steel presents the best option from a sustainability and availability perspectives for all the metals and in increase in Corrosion Resistance would significantly increase the Durability and overall score of this material. However, it is essential to evaluate the Economics, Sustainability and Future Availability of the desired protection method to ensure that the addition of a coating or anode does not significantly decrease individual scores of the carbon steel. For instance, thermally sprayed aluminum coatings are often employed for corrosion protection of submerged steel components (*330, 331*). As this coating contains aluminum and an organic sealant (based on petroleum) the availability issues associated with these raw materials need to be taken into account when evaluating the long-term potential for this specific coating.

Concerning the EI of Production, increased recycling is the main approach to eliminate these impacts. A major issue for recycling of metals in general is the difficulty of separating the individual alloying elements in the scrap metal. Therefore, the development of chemical or physical processes along with on-line analytical methods for this separation presents a high-potential research area. Such technologies could not only increase the Sustainability of carbon steels and other metal alloys, but also strongly mitigate availability concerns for certain essential alloying elements such as chrome, nickel or vanadium.

5.5.5.2 Concrete

For concretes with steel rebar corrosion also presents an issue (although not as severe as for carbon steels). For blended cement concrete an effective SCM to increase corrosion resistance is GBFS. GBFS is the main addition to Portland cement used to create CEM III cement. However global demand for GBFS dramatically exceeds supply. Therefore, large multinational research projects are investigating the replacement of GBFS with calcined clays, which are available in exhaustive amounts globally. Although the investigations into the use of clays instead of GBFS are still ongoing results indicate that this substitution should be achievable without any detrimental effect on mechanical or durability performance of the concrete (*233*, *395*). AAC also have an availability issue as, next to GBFS, FA is usually used as the solid precursor material. FA is a waste product stemming from power production in coal power plants. As such power plants should be phased out in the longer term due to increased efforts to reduce global emissions the availability of FA may become critical. Furthermore, FA is also used as an SCM in blended cement, which is produced in such large quantities, that already today FA demand strongly exceeds overall supply (*233*). Therefore, research into AAC concretes based on other widely available natural pozzolans is being conducted as well. As these availability issues for GBFS and FA are already well known the Future Availability of the corresponding concretes was already rated for the new substitute materials (ex. calcined clays), which is why they do not show up as weak points in the ranking. For CSA cement raw material availability per se is not an issue, however competition for bauxite may become significant. Therefore, again research aiming at substituting bauxite with another source for the required aluminate presents a research area which may provide a long-term benefit to the use of CSA as an alternative cement type.

Next to these issues mainly related to Growth of Competing Industries (weight 2), the main weakness of all concretes analyzed is the Recycling Approach (weight 3). To address this issue extensive policy measures (see next section) as well as technological developments will be necessary to move from today's landfilling and downcycling practices to at least partial recycling. The main technical problem to date is the recycling of the fine fraction recovered from demolished concrete. This fraction contains hardened cement, sand and light contaminants such as wood, plastics, and foams. In order to reuse the hardened cement as a limestone substitute in a cement kiln a process will need to be developed to separate the cement from sand and other contaminants. Such processes are currently in development and show very promising first results (*390, 391*). As the recycled cement could be used to replace only low-quality limestone in the cement kiln, the future recycling potential for concrete is substantial but there exists a limitation on the possibility to replace virgin material (*421*). Additionally, investigations into the effect of combining recycled fractions from different cement types may further increase the efficiency of concrete recycling as it would allow the use of a single facility for the recycling of numerous concrete mixtures. The development of such technologies and study of recycled concrete properties, also for the alternative cement types, presents a promising area of investment considering the potential long term environmental and economic benefits of efficient concrete recycling on a global level.

5.5.5.3 Carbon Fiber Reinforced Polymer Composites

As mentioned CFRP composites not only present a promising option for structural components but also a highly corrosion resistant alternative to standard steel rebar in concrete. The low UV resistance (weight 1) which presents a minor issue for exposed components naturally is of no relevance for the covered rebar. The biggest issue for CF is their total dependence on fossil fuel as a resource and low recyclability (weight 3). Both of these issues can be addressed through increased efforts aimed at developing CFs from natural, renewable resources such as cellulose and lignin or bio-based pitch. An overview of recent developments can be found in Ogale et al. (*424*). A major obstacle in the development of such bio-based CFs is that the fibers produced from renewable precursors are significantly weaker than those produced from polyacrylonitrile (PAN). Overcoming these deficiencies would allow the use of bio-based CFs for general construction. A consequence of increased effort and investment in this area would be increased renewability (weight 2), a lower EI of Production (weight 2), decreased need for full recycling (weight 3) - as the raw materials are renewable - and furthermore an increase in global CF production volume, which would mitigate the expected competition for this material from different industries with a high demand growth (weight 2). Therefore, such a development could greatly increase the overall score of CFRPs and make them extremely competitive when compared to the other analyzed materials.

Another approach with an impact on multiple attributes is the development of alternative matrices. The ideal matrix has low water absorption, creates a strong interfacial bond with the CFs (both leading to a high moisture resistance, weight 3) and can be removed from the fibers under relatively mild conditions, which do not cause damage to the CFs themselves (leading to a higher recycling score, weight 3). Funding research on such developments will further increase the cost effectiveness and sustainability of using CFRPs for marine construction, which in the long term may provide significant economic potential for suppliers of these materials.

5.5.5.4 Timber

The strengths of all the timbers analyzed is as mentioned their renewability and associated availability. However, to enable large scale use of these sustainable materials for construction in the marine environment the main issues that need to be addressed are the low Resistance to Degradation by Marine Organisms (weight 3) and low Moisture Resistance (weight 3). Impregnation with biocides is commonly used approach to increase timbers resistance to biological degradation. However, increasingly stringent environmental regulations may severely limit the applicability of broadly active biocides in the future. The development of environmentally friendly protective coatings may provide an alternative which not only addresses biological but also moisture resistance. However, to ensure efficacy coatings need to be completely intact for long periods of time, as even small defects provide openings for moisture or organisms to reach the timber underneath. Furthermore, it must again be kept in mind, that the application of such coatings may not strongly affect the positive availability scores of timber. A more promising approach to increasing the resistance of more widely available timber species is through chemical or thermal modification. The advantage of these two techniques is that the modified timber does not leach any harmful substances into the environment and can be recycled or disposed of in the same way as untreated timber. A promising example is furfurylation, which uses furfural alcohol produced from agricultural waste (a renewable raw material) to increase biological resistance, modulus and hardness of timber. This result in timber suitable for applications under use class 4 (*425–427*). Another example is mineralization which alters the mechanical structure of timber components to resemble that of the more durable tropical hardwoods (*428*). Although further development will be necessary to achieve a durability suitable for use class 5, which corresponds to marine environments, investments into such technologies have a high potential to pay off in the long term as they will further increase the adoption of timber-based products for large scale construction. Further secondary research foci that may enable and will also profit from increased use of timbers for large scale construction are joining technologies (related to Ease of Manufacture, weight 1) and fire resistance improving coatings or manufacturing processes (weight 2).

5.5.6 Focus Areas for Policy Measures

For the weak points of each material mentioned in the previous subsection certain improvements cannot be provided by technological or material developments alone. Here it is possible for governments to enable sustainability improvements not only be funding the previously discussed research areas, but also by the implementation of targeted policies.

Across the entire spectrum of analyzed materials it is essential for governments to actively increase recycling rates in order to decrease the EI of Production (based on the use of virgin material) as well as the dependence on natural raw material resources. This can be achieved on one-hand through investments into suitable recycling infrastructure, increases in land-fill taxes and providing incentives for the use of recycled materials (*393, 421*). On the other hand, however, it will also require changes to current building codes and regulations to allow for the use of recycled materials (esp. for concrete) without any penalties (ex. higher safety factors when using recycled aggregate) compared to virgin materials. Naturally, such codes need to be founded on experimental evidence. Therefore, another promising government action is the sponsoring of pilot projects and research programs to determine the long-term real-life performance of recycled materials. Due to the risk associated with such projects, it is highly unlikely that private companies will develop them on their own. Such projects and changes in building codes are also necessary to increase the competitiveness of alternative rebar types, cements, and also the FRPs as a whole. These materials currently all have a high uncertainty, but a potential advantage concerning sustainability, and availability compared to established materials (blended cement and steel) and therefore their adoption by the industry could greatly contribute to increasing the sustainability of marine construction practices.

For timber, the most impactful government policies must be aimed at ensuring sufficient supply of sustainably sourced material. Ensuring that timber is only sourced from certified managed forest areas is a first necessary step to allow the use of timber to reach its full upside potential (Sustainability and Future Availability). Additionally, governments around the world should already today consider expansion of sustainably managed forest areas in order to be able to meet the increase in demand that is expected for the coming decades (*419*). Such an expansion requires extremely long-term planning which most likely exceeds the horizons which are acceptable for private companies to generate a return on investments. Therefore, such developments will initially need to be publicly funded. A measure with more direct impact on the use of timber in construction is the adaption of existing fire safety codes to reflect the significant advances in timber fire safety management/predictability of the last decade (*429*, *430*).

6 Conclusion and Outlook

In the scope of this thesis a comprehensive chain of cause and effect connecting individual trends and megatrends was developed, with the goal of identifying the major issues that will arise in the coming decades, determining an industry capable of addressing these issues on a global scale and developing a framework to allow this industry to prepare for these changes by focusing research and policy efforts towards projects and concepts with the potential for promising results on a large scale and also for a long period of time.

After presenting a complete overview and categorization of existing trends and megatrends the connections between these individual developments were established. The continued growth of global population and increasing rate of urbanization were identified to lie at the heart of the major challenges facing humanity in the coming decades. Climate change as one of these grand challenges will have severe effects on the wellbeing of billions of people around the world, either directly, through for instance rising sea levels and increasingly frequent extreme weather events, and indirectly through increasing global conflict potential. It was argued that, along with other more established mitigation and adaption strategies, floating construction may form a crucial piece of a possible solution.

The actual materials employed for the construction of infrastructure in the aggressive marine environment were determined to present a key component enabling the sustainable growth of this industry in the long term. Enabling the development of suitable construction materials that are durable, economic to use, sustainable, safe and readily available in the long-term future was therefore set as the goal of the framework that was developed in the scope of the thesis. As the marine construction industry only represents a portion of the general construction industry, the framework was designed to be applicable to the entire construction industry covering many different types of materials and environments.

This final framework is based on a holistic ranking of materials' technical, economic and environmental performance as well as the future availability of their respective raw material constituents. This detailed evaluation enables a comparison of the strengths and weaknesses of existing as well as newly developed materials. Each of the 27 attributes included in the framework is measured on a precisely defined scale, which is based on literature and expert data, and presented in detail. Thus, an objective and efficient evaluation of individual materials by practitioners and researchers is possible. Combining the evaluation of material performance with the analysis of factors affecting the respective long-term availability, it is possible to focus funding on specific areas and approaches where research and policy measures have the highest probability of providing long-term improvements to the construction industry.

In order to demonstrate the applicability of the framework it was applied to the specific case of marine construction and used to rank and evaluate a total of 48 different materials from four different material categories including metals, fiber reinforced polymer composites, concrete and timber. Each material category was first analyzed on its own to determine the strengths and weaknesses of each material, identify those most suitable for sustainable marine construction in the long-term future and evaluate potential research and development projects as well as policy measures.

The comparison of different types of metal alloys, resulted in carbon steels achieving the highest score followed by titanium alloys, aluminum alloys, nickel-copper alloys and finally stainless steels. For the lower ranked alloy types the higher Durability scores could not compensate for the Future Availability concerns of various specialized alloying elements (ex. Ni, Cr, V, Mo). The main weakness of carbon steels is their low corrosion resistance, which however is compensated by a low price and high availability. The critical research areas identified were the development of environmentally friendly protective coatings for carbon steels and improved separation and recycling technologies, in order to minimize contaminants in the recycled materials, for all metal alloys. While many such technologies already exist, they are currently still uneconomical on a large scale. Further investments into their development may in the long-term enable a significantly more sustainable use of metals not only in marine construction but also for all other areas of application.

Chapter 5.2 covered the ranking of the FRPCs. The best ranked materials were the CF composites followed by BF and GF composites. The lowest scores were achieved by NF composites mainly due to their low mechanical strength and lower chemical resistance. Concerning the matrix material, E and VE displayed a similar performance followed by the cheaper and less resistant PE and TP resins. Next to the improvement options geared towards NF composites covered in the described section, there exist many further research areas aiming at improving the performance of composites with all fiber types for the use in marine construction, such as increasing moisture and fire resistance. These research areas will be essential to develop composites that are stable and durable in the extreme conditions present in the marine environment.

For the concretes, the best scores were achieved by BC and AAC concrete, CSA concrete scored slightly lower mainly due to the increased demand for bauxite as a raw material. CFRP rebar showed a marginally better performance than CS and GFRP rebar which are both significantly better than SS. The main weaknesses of all evaluated concretes are the currently still very low recycling rates and supply issues of specific raw materials required for clinker production. The accelerated adaption of existing construction codes and standards to recent empirical findings in order to encourage recycling and the use of alternative materials was identified as an essential step to address these issues. Despite the varying scores, in reality all discussed cement and rebar types will be used in the future, making the selection of the most suitable and sustainable material for specific cases strongly dependent on local raw material availability and environmental conditions.

Finally, the evaluation of the different timber types, showed non-tropical hardwood timbers to be the highest scoring material, while softwoods and tropical hardwoods both achieved a similar but lower score. In general what can be said for the timbers is that, while suffering from a relatively low durability and mediocre economic performance, the low EI of production, renewability and consequently high future availability make them an exceedingly promising material for sustainable construction in the long-term future. Nevertheless, in order to achieve more widespread application the main weaknesses such as a low moisture and biological resistance and the long time frames required for production increases need to be further addressed through for instance the development of environmentally friendly coatings, and the development of long-term plans for managed forests factoring in the expected rise in demand for large scale timber components.

After these material category specific evaluations, the systematic comparison of all materials produced a final ranking showing timber, concrete, carbon fiber reinforced polymers and also steel to be the highest scoring materials when considering long term availability as the most important factor. For these materials high potential research areas identified were the development of environmentally friendly protective coatings and improved recycling technologies. The funding of specific pilot projects demonstrating the use of recycled and alternative materials in large scale construction and incentivization of recycling operations are considered as impactful policy measures.

The presented results clearly demonstrate the usefulness of the employed framework. In a further step the high-level prioritization of research areas and policy measures could be further developed in order to enable well informed funding decisions. For instance, the different options for improving material durability could be evaluated using the framework to rank the properties of a specific material with a specific protection method applied, in order to identify the approach with the highest overall value. Furthermore, the materials ranked present an initial selection which could be expanded for instance with cross laminated timbers or different more specific metal alloys.

It needs to be stated that this ranking does not apply to any component specific material selection decisions in marine construction. For such decision more appropriate, and precisely measurable attributes need to be defined. Furthermore, for immediate construction in the present an analysis of future developments is superfluous. The ranking would also naturally produce different results if alternative weighting factors were used to represent other desired cases. Using the data presented in Appendix A, this could be done very quickly for the analyzed materials. Further application of the framework by practitioners and researchers to other materials and use cases, would also lead to the development of a growing materials database, which could quickly provide crucial information on impactful material development directions, policy options and criticality issues, not only for research institutions and governments but for the entire construction industry.

7 References

1. J. Naisbitt, *Megatrends: Ten new directions transforming our lives* (Warner Books, New York, 1982).
2. K. Cuhls, A. Bunkowski, L. Behlau, Fraunhofer future markets. *Science and Public Policy*. **39**, 232–244 (2012), doi:10.1093/scipol/scs018.
3. R. Klingner, L. Behlau, M. Spengel, A. VIdal, in *The 3rd international Seville conference on Future-oriented Technology Analysis (FTA), Impacts and implications for policy and decision making : book of abstracts*, T.-T. T. Könnölä, P. Desruelle, X. Goenaga Beldarrain, Eds. (Publications Office, Luxembourg, 2008).
4. European Commission, *The world in 2025, Rising Asia and socio-ecological transition* (Office for Official Publications of the European Communities, Luxembourg, 2009).
5. Verband Der Chemischen Industrie e.V., „Die deutsche Chemische Industrie 2030“. (Verband Der Chemischen Industrie e.V., 2013; https://www.vci.de/vci/downloads-vci/publikation/langfassung-prognos-studie-30-01-2013.pdf).
6. H. Utikal, J. Woth, From megatrends to business excellence: Managing change in the German chemical and pharmaceutical industry. *Journal of Business Chemistry*. **12**, 41–47 (2015).
7. The Millennium Project, *15 Global Challenges* (10.01.2015) (available at http://www.millennium-project.org/millennium/challenges.html).
8. R. C. Valencia, *The Future of the Chemical Industry by 2050* (John Wiley & Sons, Weinheim, Germany, 2013).
9. United Nations, Department of Economic and Social Affairs, Population Division, “World Population Prospects: The 2015 Revision, custom data acquired via website”. (United Nations, 2015; http://esa.un.org/unpd/wpp/DataQuery/).
10. United Nations, Department of Economic and Social Affairs, Population Division, “World Population Prospects: The 2015 Revision, Key Findings and Advanced Tables”. (2015).
11. Bundeszentrale für politische Bildung, *Altersstruktur und Bevölkerungsentwicklung* (available at http://www.bpb.de/nachschlagen/zahlen-und-fakten/europa/70503/altersstruktur).
12. V. Hessel, Megatrends – megascience? *Green Processing and Synthesis*. **3** (2014), doi:10.1515/gps-2014-0021.

13. V. Reichl, C. Krys, K. Dengler, "Roland Berger Trend Compendium 2030 - Trend 2 Globalization and future markets". (Roland Berger, 2014; http://www.rolandberger.com/media/pdf/Roland_Berger_Trend_Compendium_2030_Trend_2_Globalization_and_future_markets_20140501.pdf).
14. United Nations, Department of Economic and Social Affairs, *World urbanization prospects, The 2014 revision : highlights* (United Nations, New York, 2014).
15. J. C. Glenn, E. Florescu, "2015-16 State of the Future Executive Summary". (The Millennium Project, 2015; http://www.millennium-project.org/millennium/2015-SOF-ExecutiveSummary-English.pdf).
16. PWC, "The World in 2050, Will the shift in globaleconomic power continue?". (PWC, 2015; https://www.pwc.com/gx/en/issues/the-economy/assets/world-in-2050-february-2015.pdf).
17. BCG, *Boston Consulting Group On Global Megatrends* (2011) (available at http://www.chemanager-online.com/en/topics/chemicals-distribution/boston-consulting-group-global-megatrends).
18. The Economist Intelligence Unit Limited, "Long-term macroeconomic forecasts Key trends to 2050". (2015; http://pages.eiu.com/rs/783-XMC-194/images/Long-termMacroeconomicForecasts_KeyTrends.pdf).
19. V. Hessel, Megatrends – megascience? *Green Processing and Synthesis*. **3** (2014), doi:10.1515/gps-2014-0069.
20. N. Freudenberg, *The 100 Largest Governments and Corporations by Revenue* (2015) (available at http://corporationsandhealth.org/2015/08/27/the-100-largest-governments-and-corporations-by-revenue/).
21. J. C. Glenn, T. J. Gordon, E. Florescu, "Executive Summary of the 2013-14 State of the Future". (The Millennium Project, 2013; http://www.millennium-project.org/millennium/2014SOF-Executive_Summary.pdf).
22. T. Ring, IT's megatrends: The security impact. *Network Security*. **2013**, 5–8 (2013), doi:10.1016/S1353-4858(13)70080-1.
23. V. Hessel, Megatrends – megascience? *Green Processing and Synthesis*. **3** (2014), doi:10.1515/gps-2014-0034.
24. Food and Agriculture Organization of the United Nations, "FAO Statistical Pocketbook 2015 World Food and Agriculture". (Food and Agriculture Organization of the United Nations, 2015).
25. N. Alexandratos, J. Bruinsma, *World agriculture towards 2030/2050: the 2012 revision* (Food and Agriculture Organization of the United Nations, Rome, 2012).

26. D. Tilman, C. Balzer, J. Hill, B. L. Befort, Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*. **108**, 20260–20264 (2011).

27. V. Reichl, C. Krys, K. Dengler, “Roland Berger Trend Compendium 2030 - Trend 3 Scarcity of resources”. (Roland Berger, 2014).

28. B. Roeffen, B. Dal Bo Zanon, K.M. Czapiewska, R. de Graaf, “Reducing global land scarcity with floating urban development and food produciton”. (blue21.nl, 2013; http://www.blue21.nl/wp-content/uploads/2015/09/Roeffen_LandScarcity.pdf).

29. E. Florescu, J. C. Glenn, Environmental Security Rising on the International Agenda. *Development, Environment and Foresight*. **1**, 6–23 (2015).

30. Food and Agriculture Organization of the United Nations, “Global food losses and food waste”. (Food and Agriculture Organization of the United Nations, 2011).

31. G. Tverberg, *BP Data Suggests We Are Reaching Peak Energy Demand* (available at https://ourfiniteworld.com/2015/06/23/bp-data-suggests-we-are-reaching-peak-energy-demand/).

32. International Energy Agency, “World Energy Outlook 2015 - Executive Summary - English Version”. (IEA, 2015).

33. Rystad Energy, *Global liquids cost curve (October 2015)* (2015) (available at http://www.rystadenergy.com/NewsEvents/PressReleases/global-liquids-supply-cost-curve).

34. International Energy Agency, “World Energy Outlook 2014 Factsheet”. (International Energy Agency, 2014).

35. R. K. Pachauri, L. Mayer, Eds., *Climate change 2014*, *Synthesis report* (Intergovernmental Panel on Climate Change, Geneva, Switzerland, 2015).

36. M. E. Hauer, J. M. Evans, D. R. Mishra, Millions projected to be at risk from sea-level rise in the continental United States. *Nature Clim Change*. **6**, 691–695 (2016), doi:10.1038/nclimate2961.

37. European Commission, *Paris Agreement - European Commission* (2016) (available at http://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm).

38. D. Y.C. Leung, G. Caramanna, M. M. Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews*. **39**, 426–443 (2014), doi:10.1016/j.rser.2014.07.093.

39. McKinsey Global Institute, “The carbon productivity challenge: Curbing climate change and sustaining growth”. (McKinsey, 2008).

40. United Nations, Department of Economic and Social Affairs, “World urbanization prospects, The 2018 revision : Key facts”. (United Nations, 2018).
41. McKinsey Global Institute, “Urban world: Mapping the economic power of cities”. (2011).
42. B. Bajželj *et al.*, Importance of food-demand management for climate mitigation. *Nature Climate change*. **4**, 924–929 (2014), doi:10.1038/nclimate2353.
43. D. K. Ray, N. D. Mueller, P. C. West, J. A. Foley, Yield Trends Are Insufficient to Double Global Crop Production by 2050. *PloS one*. **8**, e66428 (2013), doi:10.1371/journal.pone.0066428.
44. R. A. Houghton, Carbon emissions and the drivers of deforestation and forest degradation in the tropics. *Current Opinion in Environmental Sustainability*. **4**, 597–603 (2012), doi:10.1016/j.cosust.2012.06.006.
45. P. Gerber, H. Steinfeld, B. Henderson, A. Mottet, C. Opio, *Tackling climate change through livestock, A global assessment of emissions and mitigation opportunities* (Food and Agriculture Organization of the United Nations (FAO), Rome, 2013).
46. S. A. Northey, G. M. Mudd, T. T. Werner, Unresolved Complexity in Assessments of Mineral Resource Depletion and Availability. *Nat Resour Res*. **27**, 241–255 (2018), doi:10.1007/s11053-017-9352-5.
47. G. M. Mudd, Gold mining in Australia. *Environmental Science & Policy*. **10**, 629–644 (2007), doi:10.1016/j.envsci.2007.04.006.
48. European Commission, “Report on Critical Raw Materials for the EU”. (2014).
49. J. Church, J. Gregory, N. White, S. Platten, J. Mitrovica, Understanding and Projecting Sea Level Change. *Oceanog.* **24**, 130–143 (2011), doi:10.5670/oceanog.2011.33.
50. D. Guha-Sapir, R. Below, P. Hoyois, *EM-DAT: The CRED/OFDA International Disaster Database* (2016) (available at www.emdat.be).
51. W. N. Adger, T. P. Hughes, C. Folke, S. R. Carpenter, J. Rockstrom, Social-ecological resilience to coastal disasters. *Science*. **309**, 1036–1039 (2005), doi:10.1126/science.1112122.
52. G.R. Brakenridge, *Global Active Archive of Large Flood Events* (2016) (available at http://floodobservatory.colorado.edu/Archives/index.html).
53. A. Smajgl *et al.*, Responding to rising sea levels in the Mekong Delta. *Nature Clim Change*. **5**, 167–174 (2015), doi:10.1038/nclimate2469.
54. S. Albert *et al.*, Interactions between sea-level rise and wave exposure on reef island dynamics in the Solomon Islands. *Environ. Res. Lett.* **11**, 54011 (2016), doi:10.1088/1748-9326/11/5/054011.

55. L. Kumar, S. Taylor, Exposure of coastal built assets in the South Pacific to climate risks. *Nature Clim Change*. **5**, 992–996 (2015), doi:10.1038/nclimate2702.

56. R. de Graaf, *Adaptive urban development, A symbiosis between cities on land and water in the 21st century* (Rotterdam University Press, Rotterdam, The Netherlands, ed. 1, 2012).

57. A. J. Challinor *et al.*, A meta-analysis of crop yield under climate change and adaptation. *Nature Climate change*. **4**, 287–291 (2014), doi:10.1038/nclimate2153.

58. C. Raleigh, H. Urdal, Climate change, environmental degradation and armed conflict. *Political Geography*. **26**, 674–694 (2007), doi:10.1016/j.polgeo.2007.06.005.

59. J. Barnett, Security and climate change. *Global Environmental Change*. **13**, 7–17 (2003).

60. P. Schwartz, D. Randall, "An abrupt climate change scenario and its implications for United States national security". (Washington, DC: Environmental Media Services, 01.01.2003).

61. C. M. Wang, Z. Y. Tay, Very Large Floating Structures. *Procedia Engineering*. **14**, 62–72 (2011), doi:10.1016/j.proeng.2011.07.007.

62. M. Lamas-Pardo, G. Iglesias, L. Carral, A review of Very Large Floating Structures (VLFS) for coastal and offshore uses. *Ocean Engineering*. **109**, 677–690 (2015), doi:10.1016/j.oceaneng.2015.09.012.

63. C. M. Wang, B. T. Wang, *Large floating structures, Technological advances* (Springer, Singapore, 2015).

64. C. J. Andrews, L. Dewey-Mattia, J. M. Schechtman, M. Mayr, in *Climate change and land policies*, G. K. Ingram, Y.-h. Hong, Eds. (Lincoln Institute of Land Policy, Cambridge Mass., 2011), pp. 91–115.

65. J. van Zalk, P. Behrens, The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. *Energy Policy*. **123**, 83–91 (2018), doi:10.1016/j.enpol.2018.08.023.

66. S.-P. Breton, G. Moe, Status, plans and technologies for offshore wind turbines in Europe and North America. *Renewable Energy*. **34**, 646–654 (2009), doi:10.1016/j.renene.2008.05.040.

67. A. R. Henderson *et al.*, Offshore Wind Energy in Europe - A Review of the State-of-the-Art. *Wind Energ.* **6**, 35–52 (2003), doi:10.1002/we.82.

68. X. Sun, D. Huang, G. Wu, The current state of offshore wind energy technology development. *Energy*. **41**, 298–312 (2012), doi:10.1016/j.energy.2012.02.054.

69. A.-K. Govindji, J. Rhodri, A. Carvallo, "Detailed appraisal of the offshore wind industry in Japan". (Carbon Trust, 2014).

70. U.S. Department of Energy, “A National Offshore Wind Strategy. Creating an Offshore Wind Energy Industry in the United States”. (U.S. Department of Energy, 2011).
71. European Wind Energy Association, “Deep water, The next step for offshore wind energy”. (European Wind Energy Association, 2013).
72. R. James, M. Costa Ros, “Floating Offshore Wind - Market & Technology Review”. (Carbon Trust, 2015).
73. L. Mofor, J. Goldsmith, F. Jones, *Ocean Energy: Technologies, Patents, Deployment Status and Outlook* (International Renewable Energy Agency, Bonn, 2014).
74. R. Kempener, F. Neumann, *Tidal Energy Technology Brief* (International Renewable Energy Agency, Bonn, 2014).
75. C. Pérez-Collazo, D. Greaves, G. Iglesias, A review of combined wave and offshore wind energy. *Renewable and Sustainable Energy Reviews*. **42**, 141–153 (2015), doi:10.1016/j.rser.2014.09.032.
76. K. Rajagopalan, G. C. Nihous, Estimates of global Ocean Thermal Energy Conversion (OTEC) resources using an ocean general circulation model. *Renewable Energy*. **50**, 532–540 (2013), doi:10.1016/j.renene.2012.07.014.
77. R. Kempener, F. Neumann, *Wave Energy Technology Brief* (International Renewable Energy Agency, Bonn, 2014).
78. R. Kempener, F. Neumann, *Ocean Thermal Energy Conversion Technology Brief* (International Renewable Energy Agency, Bonn, 2014).
79. A. F. d. O. Falcão, Wave energy utilization. *Renewable and Sustainable Energy Reviews*. **14**, 899–918 (2010), doi:10.1016/j.rser.2009.11.003.
80. R. Pelc, R. M. Fujita, Renewable energy from the ocean. *Marine Policy*. **26**, 471–479 (2002), doi:10.1016/S0308-597X(02)00045-3.
81. C. Kalogeri *et al.*, Assessing the European offshore wind and wave energy resource for combined exploitation. *Renewable Energy*. **101**, 244–264 (2017), doi:10.1016/j.renene.2016.08.010.
82. M. Ghadiryanfar, K. A. Rosentrater, A. Keyhani, M. Omid, A review of macroalgae production, with potential applications in biofuels and bioenergy. *Renewable and Sustainable Energy Reviews*. **54**, 473–481 (2016), doi:10.1016/j.rser.2015.10.022.
83. J. M. Adams, J. A. Gallagher, I. S. Donnison, Fermentation study on Saccharina latissima for bioethanol production considering variable pre-treatments. *J Appl Phycol*. **21**, 569–574 (2009), doi:10.1007/s10811-008-9384-7.
84. Food and Agriculture Organization of the United Nations, “The State of World Fisheries and Aquaculture, Contributing to food security and nutrition for all”. (FAO, 2016).

85. M. N. Kutty, World food crisis, FAO alert and India. *World aquaculture*. **41**, 6–7 (2010).
86. M. Troell *et al.*, Does aquaculture add resilience to the global food system? *Proceedings of the National Academy of Sciences of the United States of America*. **111**, 13257–13263 (2014), doi:10.1073/pnas.1404067111.
87. C. M. Duarte *et al.*, Will the Oceans Help Feed Humanity? *BioScience*. **59**, 967–976 (2009), doi:10.1525/bio.2009.59.11.8.
88. T. Gjedrem, N. Robinson, M. Rye, The importance of selective breeding in aquaculture to meet future demands for animal protein. *Aquaculture*. **350-353**, 117–129 (2012), doi:10.1016/j.aquaculture.2012.04.008.
89. L. R. Brown, in *State of the World 1999*, L. Starke, Ed. (W.W. Norton & Company, New York, 1999), pp. 115–132.
90. L. R. Brown, in *State of the World 2001*, L. Starke, Ed. (W.W. Norton & Company, New York, 2001), pp. 43–62.
91. A. McManus, W. Newton, *Seafood, nutrition and human health: A synopsis of the nutritional benefits of consuming seafood* (Centre of Excellence Science Seafood & Health , Curtin Health Innovation Research Institute, Curtin University of Technology, Perth, 2011).
92. M. C. J. Verdegem, R. H. Bosma, J. A. J. Verreth, Reducing Water Use for Animal Production through Aquaculture. *International Journal of Water Resources Development*. **22**, 101–113 (2006), doi:10.1080/07900620500405544.
93. K. Grigorakis, G. Rigos, Aquaculture effects on environmental and public welfare - the case of Mediterranean mariculture. *Chemosphere*. **85**, 899–919 (2011), doi:10.1016/j.chemosphere.2011.07.015.
94. J. Marra, When will we tame the oceans? *Nature*. **436**, 175–176 (2005), doi:10.1038/436175a.
95. M. F. Addis *et al.*, Proteomic analysis of muscle tissue from gilthead sea bream (Sparus aurata, L.) farmed in offshore floating cages. *Aquaculture*. **309**, 245–252 (2010), doi:10.1016/j.aquaculture.2010.08.022.
96. B. Pogoda, B. H. Buck, W. Hagen, Growth performance and condition of oysters (Crassostrea gigas and Ostrea edulis) farmed in an offshore environment (North Sea, Germany). *Aquaculture*. **319**, 484–492 (2011), doi:10.1016/j.aquaculture.2011.07.017.
97. T. L. Sveälv, Inshore versus offshore farming. *Aquacultural Engineering*. **7**, 279–287 (1988), doi:10.1016/0144-8609(88)90027-1.

98. Food and Agriculture Organization of the United Nations, “Aquaculture development, 4. Ecosystem approach to aquaculture” *FAO technical guidelines for responsible fisheries, 1020-5292.* (Food and Agriculture Organization of the United Nations, 2010).
99. G. F. Loverich, A Case Study of an Offshore SeaStation® Sea Farm. *mar technol soc j*. **44**, 36–46 (2010), doi:10.4031/MTSJ.44.3.2.
100. S. O. Olanrewaju, A. Magee, A.S.A. Kader, K. F. Tee, Simulation of offshore aquaculture system for macro algae (seaweed) oceanic farming. *Ships and Offshore Structures*, 1–10 (2016), doi:10.1080/17445302.2016.1186861.
101. C. Stevens, D. Plew, N. Hartstein, D. Fredriksson, The physics of open-water shellfish aquaculture. *Aquacultural Engineering*. **38**, 145–160 (2008), doi:10.1016/j.aquaeng.2008.01.006.
102. O. O. Sulaiman *et al.*, Mooring analysis for very large offshore aquaculture ocean plantation floating structure. *Ocean & Coastal Management*. **80**, 80–88 (2013), doi:10.1016/j.ocecoaman.2013.02.010.
103. SalMar ASA, *Offshore Fish Farming – a new era!* - (25.08.2016) (available at http://www.salmar.no/en/offshore-fish-farming-a-new-era).
104. B. Hersoug, The greening of Norwegian salmon production. *Maritime Studies*. **14**, 481 (2015), doi:10.1186/s40152-015-0034-9.
105. C. M. Beal *et al.*, Algal biofuel production for fuels and feed in a 100-ha facility. *Algal Research*. **10**, 266–279 (2015), doi:10.1016/j.algal.2015.04.017.
106. International Renewable Energy Agency, “Boosting Biofuels”. (International Renewable Energy Agency (IRENA), 2016).
107. K. Samarakoon, Y.-J. Jeon, Bio-functionalities of proteins derived from marine algae — A review. *Food Research International*. **48**, 948–960 (2012), doi:10.1016/j.foodres.2012.03.013.
108. A. J. Smit, Medicinal and pharmaceutical uses of seaweed natural products. *Journal of Applied Phycology*. **16**, 245–262 (2004), doi:10.1023/B:JAPH.0000047783.36600.ef.
109. S. Abinandan, S. Shanthakumar, Challenges and opportunities in application of microalgae (Chlorophyta) for wastewater treatment. *Renewable and Sustainable Energy Reviews*. **52**, 123–132 (2015), doi:10.1016/j.rser.2015.07.086.
110. B. Dal Bo Zanon, B. Roeffen, K. M. Czapiewska, R. E. de Graaf-Van Dinther, P. R. Mooij, Potential of floating production for delta and coastal cities. *Journal of Cleaner Production*. **151**, 10–20 (2017), doi:10.1016/j.jclepro.2017.03.048.

111. R. D. Kinley, R. de Nys, M. J. Vucko, L. Machado, N. W. Tomkins, The red macroalgae Asparagopsis taxiformis is a potent natural antimethanogenic that reduces methane production during in vitro fermentation with rumen fluid. *Anim. Prod. Sci.* **56**, 282 (2016), doi:10.1071/AN15576.
112. S. Kesteven, *Will feeding cows seaweed help save the planet?* (19.10.2016) (available at http://www.abc.net.au/news/2016-10-19/environmental-concerns-cows-eating-seaweed/7946630?pfmredir=sm).
113. M. Battaglia, *Seaweed could hold the key to cutting methane emissions from cow burps* (2016) (available at https://theconversation.com/seaweed-could-hold-the-key-to-cutting-methane-emissions-from-cow-burps-66498).
114. A. Bergheim, Recent growth trends and challenges in the Norwegian aquaculture industry. *lajar*. **40**, 800–807 (2012), doi:10.3856/vol40-issue3-fulltext-26.
115. R. L. Naylor *et al.*, Effect of aquaculture on world fish supplies. *Nature*. **405**, 1017–1024 (2000).
116. R. L. Naylor *et al.*, Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences of the United States of America*. **106**, 15103–15110 (2009), doi:10.1073/pnas.0905235106.
117. W. Boomsma, J. Warnaars, in *2015 IEEE Underwater Technology (UT)* (IEEE, 2015), pp. 1–4.
118. J. R. Hein, K. Mizell, A. Koschinsky, T. A. Conrad, Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geology Reviews*. **51**, 1–14 (2013), doi:10.1016/j.oregeorev.2012.12.001.
119. ECORYS, “Study to investigate the state of knowledge of deep-sea mining”. (2014; https://webgate.ec.europa.eu/maritimeforum/sites/maritimeforum/files/FGP96656_final_rep._formatted._november_2014.pdf).
120. J. Laugesen, Some reflections related to reducing environmental impacts from deep sea mining, Trondheim, Norway, 10 May 2016.
121. S. Petersen, A. Krätschell, M. D. Hannington, “The Current State of Global Activities Related to Deep-sea Mineral Exploration and Mining” *EAGE/DGG Workshop on Deep Mineral Exploration.* (2016).
122. E. Ramirez-Llodra *et al.*, Man and the last great wilderness. *PloS one*. **6**, e22588 (2011), doi:10.1371/journal.pone.0022588.
123. C. L. van Dover, Tighten regulations on deep-sea mining. *Nature*. **470**, 31–33 (2011), doi:10.1038/470031a.

124. A. Vanreusel, A. Hilario, P. A. Ribeiro, L. Menot, P. M. Arbizu, Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. *Scientific reports*. **6**, 1–6 (2016), doi:10.1038/srep26808.

125. D. L. Chandler, *Floating nuclear plants could ride out tsunamis* (2014) (available at http://news.mit.edu/2014/floating-nuclear-plants-could-ride-out-tsunamis-0416).

126. Siemens, *Floating Power Plants* (02.08.2016) (available at http://www.siemens.com/innovation/en/home/pictures-of-the-future/energy-and-efficiency/sustainable-power-generation-power-ship-japan.html).

127. K. Olthuis, D. Keuning, *Float!, Building on water to combat urban congestion and climate change* (Frame, Amsterdam, 2010).

128. E. Watanabe, C.M. Wang, T. Utsunomiya, T. Moan, *Very Large Floating Structures: Applications, Analysis and Design* (Centre for Offshore Research and Engineering National University of Singapore, Singapore, 2004).

129. N. Lister, E. Muk-Pavic, Sustainable artificial island concept for the Republic of Kiribati. *Ocean Engineering*. **98**, 78–87 (2015), doi:10.1016/j.oceaneng.2015.01.013.

130. K. Wyett, Escaping a Rising Tide. *Asia and the Pacific Policy Studies*. **1**, 171–185 (2014), doi:10.1002/app5.7.

131. B.W. Eakins, G.F. Sharman, “Volumes of the World’s Oceans from ETOPO1”. (NOAA National Geophysical Data Center, 2010).

132. V. Monier *et al.*, “Study on the management of construction and demolition waste in the EU, Contract 07.0307/2009/540863/SER/G2, Final report for the European Commission” *2009.* (Bio Intelligence Service S.A.S., 2011).

133. H. Dahlbo *et al.*, Construction and demolition waste management – a holistic evaluation of environmental performance. *Journal of Cleaner Production*. **107**, 333–341 (2015), doi:10.1016/j.jclepro.2015.02.073.

134. H. Wu *et al.*, Demolition waste generation and recycling potentials in a rapidly developing flagship megacity of South China. *Construction and Building Materials*. **113**, 1007–1016 (2016), doi:10.1016/j.conbuildmat.2016.03.130.

135. L. Z. Hales, “Floating breakwaters: State of the art, literature review”. (USACE, 1981;http://resolver.tudelft.nl/uuid:9c654831-6d09-4470-b175-d7c308e89ff5).

136. FDN Group, *Floating Breakwater in Monaco* (available at https://www.fdn-engineering.nl/floating-breakwater-in-monaco).

137. Mitsubishi Heavy Industries Ltd, *Kami-goto floating oil storage facility* (05.08.2016) (available at https://www.mhi-global.com/products/detail/oil_storage_terminal_kami-goto.html).

138. A. J. Baird, D. Rother, Technical and economic evaluation of the floating container storage and transhipment terminal (FCSTT). *Transportation Research Part C: Emerging Technologies*. **30**, 178–192 (2013), doi:10.1016/j.trc.2012.12.013.
139. American Petroleum Institute, “Offshore Access to Oil and Natural Gas Resources”. (American Petroleum Institute, 2015).
140. Offshore Technology, *Aasta Hansteen Gas Field, North Sea* (available at http://www.offshore-technology.com/projects/luva-gas-field-north-sea/).
141. IEEE Spectrum, *Japan Building World’s Largest Floating Solar Power Plant* (available at http://spectrum.ieee.org/energywise/energy/renewables/japan-building-worlds-largest-floating-solar-power-plant).
142. Research and Markets, “Global Floating Solar Panels Market Size, Market Share, Application Analysis, Regional Outlook, Growth Trends, Key Players, Competitive Strategies and Forecasts, 2016 to 2023”. (2016;https://www.researchandmarkets.com/reports/4313328/global-floating-solar-panels-market-size-market).
143. Global Wind Energy Council, “Offshore Wind”. (2016).
144. A. Smith, T. Stehly, W. Musial, “2014-2015 Offshore Wind Technologies Market Report”. (National Renewable Energy Laboratory, 2015;https://www.nrel.gov/docs/fy15osti/64283.pdf).
145. Ernst & Young, “Offshore Wind in Europe, Walking the Tightrope to Success”. (2015).
146. M. Bilgili, A. Yasar, E. Simsek, Offshore wind power development in Europe and its comparison with onshore counterpart. *Renewable and Sustainable Energy Reviews*. **15**, 905–915 (2011).
147. E. Rusu, Evaluation of the Wave Energy Conversion Efficiency in Various Coastal Environments. *Energies*. **7**, 4002–4018 (2014), doi:10.3390/en7064002.
148. Ocean Energy, *Gallery* (available at http://oceanenergy.ie/gallery/).
149. WaveDragon, *Specifications* (available at http://www.wavedragon.net/index.php?option=com_content&task=view&id=7&Itemid=7).
150. State of Green, *Wave Dragon* (available at https://stateofgreen.com/en/profiles/wave-dragon-aps).
151. International Renewable Energy Agency, “Ocean Thermal Energy Conversion Technology Brief”. (International Renewable Energy Agency, 2014).
152. Offshorewind.biz, *Norway: ANDRITZ Increases Stake in Hammerfest Strøm* (available at http://www.offshorewind.biz/2012/03/07/norway-andritz-increases-stake-in-hammerfest-strom/).

153. Offshorewind.biz, *Tidal Energy Platform to Float Off Dutch Coast* (available at http://www.offshorewind.biz/2014/10/29/tidal-energy-platform-to-float-off-dutch-coast/).
154. Lokeheed Martin, "Ocean Thermal Energy Conversion, Renewable and Stable Power for Energy Needs of Today and Tomorrow". (Lokeheed Martin, 2015).
155. International Renewable Energy Agency, "Ocean Thermal Energy Conversion". (International Renewable Energy Agency, 2014).
156. European Union - Ocean Energy Association, "Oceans of Energy. European Ocean Energy Roadmap 2010 - 2050". (2010).
157. O. Ellabban, H. Abu-Rub, F. Blaabjerg, Renewable energy resources. *Renewable and Sustainable Energy Reviews*. **39**, 748–764 (2014), doi:10.1016/j.rser.2014.07.113.
158. D. Klinger, R. Naylor, Searching for Solutions in Aquaculture. *Annu. Rev. Environ. Resour.* **37**, 247–276 (2012), doi:10.1146/annurev-environ-021111-161531.
159. Ocean Conservancy, "Right from the start-open-ocean aquaculture in the United States". (2011).
160. Washington State Department of Transportation, *SR 520 - Floating Bridge Facts* (available at https://www.wsdot.wa.gov/Projects/SR520Bridge/About/BridgeFacts.htm).
161. Washington State Department of Transportation, *SR 520 - Budget and Performance* (available at http://www.wsdot.wa.gov/Projects/SR520Bridge/Budget.htm).
162. Kansai Design Company, *Movable Floating Bridge* (available at http://kansai-design.co.jp/en/project/project01_002.html).
163. Statens vegvesen, "Project Overview Coastal Highway E39". (2011).
164. P. Tveit, Submerged floating tunnels (SFTs) for Norwegian fjords. *Procedia Engineering*. **4**, 135–143 (2010), doi:10.1016/j.proeng.2010.08.016.
165. B. Jakobsen, Design of the Submerged Floating Tunnel operating under various conditions. *Procedia Engineering*. **4**, 71–79 (2010), doi:10.1016/j.proeng.2010.08.009.
166. H. Suzuki, Overview of Megafloat. *Marine Structures*. **18**, 111–132 (2005), doi:10.1016/j.marstruc.2005.07.006.
167. M. Ros, *Floating airports: Are they about to happen?* (2016) (available at http://edition.cnn.com/2016/07/03/aviation/floating-airports/).
168. H. Sasajima, Mega-Float - Results of Phase-2 Research -. *The Twelfth International Offshore and Polar Engineering Conference, 26-31 May, Kitakyushu, Japan* (2002).
169. Ocean Pools WA, *Building on water saves space* (available at https://oceanpoolswa.com/2013/09/29/building-on-water/).

170. R. de Graaf, *Innovations in urban water management to reduce the vulnerability of cities: feasibility, case studies and governance* (TU Delft, Delft University of Technology, 2009).
171. King Pacific Lodge, *A West Coast Fishing Lodge to Remember!* (available at http://kingpacificlodge.com/the-lodge/).
172. Jumbo Kingdom (available at http://www.jumbokingdom.com/eng/profile.php).
173. KCAP Architects&Planners, *Floating Park for Rotterdam's Rijnhaven harbour* (2013) (available at http://www.kcap.eu/en/news/2013/floating_park_for_rotterdam_s_rijnhaven_harbour).
174. S. Freund, *The Chicago Riverwalk will soon feature floating garden islands* (2016) (available at https://www.timeout.com/chicago/blog/the-chicago-riverwalk-will-soon-feature-floating-garden-islands-081716).
175. I. Mulcahey, *London doesn't need a floating park on the Thames, but would it benefit from one?* (2011) (available at http://www.gensleron.com/cities/2011/10/27/london-doesnt-need-a-floating-park-on-the-thames-but-would-i.html).
176. L. Wang, *Innovative urban park in Copenhagen floats nature-infused aquatic islands* (2016) (available at http://inhabitat.com/innovative-urban-park-in-copenhagen-floats-nature-infused-aquatic-islands/).
177. M. E. Q. Pilson, *An introduction to the chemistry of the sea* (Cambridge University Press, Cambridge, 2013).
178. M. Alexander, *Marine Concrete Structures, Design, Durability and Performance* (Woodhead Publishing, Cambridge, MA, 2016).
179. C. Powell, R. Francis, *The corrosion performance of metals for the marine environment, A basic guide / edited by Carol Powell & Roger Francis* (Maney, Leeds, 2012).
180. U. M. Angst *et al.*, Present and future durability challenges for reinforced concrete structures. *Mater. Corros.* **63**, 1047–1051 (2012), doi:10.1002/maco.201206898.
181. H. Díaz, J.M. Rodrigues, C. Guedes Soares, in *Progress in Renewable Energies Offshore, Proceedings of the 2nd International Conference on Renewable Energies Offshore (RENEW2016), Lisbon, Portugal, 24-26 October 2016*, C. Guedes Soares, Ed. (CRC Press, Boca Raton, 2016), pp. 843–850.
182. World Economic Forum, "Shaping the Future of Construction – A Landscape in Transformation: An Introduction". (World Economic Forum, 2016).
183. D. C. Wilson, *Global waste management outlook* (United Nations Environment Programme, Nairobi, Kenya, 2015).

184. D. J. Harris, A quantitative approach to the assessment of the environmental impact of building materials. *Building and Environment*. **34**, 751–758 (1999), doi:10.1016/S0360-1323(98)00058-4.

185. N. Huberman, D. Pearlmutter, A life-cycle energy analysis of building materials in the Negev desert. *Energy and Buildings*. **40**, 837–848 (2008), doi:10.1016/j.enbuild.2007.06.002.

186. C. Thormark, The effect of material choice on the total energy need and recycling potential of a building. *Building and Environment*. **41**, 1019–1026 (2006), doi:10.1016/j.buildenv.2005.04.026.

187. M. Antoni, J. Rossen, F. Martirena, K. Scrivener, Cement substitution by a combination of metakaolin and limestone. *Cem. Concr. Res.* **42**, 1579–1589 (2012), doi:10.1016/j.cemconres.2012.09.006.

188. International Energy Agency, *Cement technology roadmap 2009, Carbon emissions reductions up to 2050* (OECD/IEA; World Business Council for Sustainable Development, Paris, Conches-Geneva, Switzerland, 2009).

189. F. Piccinno, R. Hischier, S. Seeger, C. Som, Eco-Efficient Process Improvement at the Early Development Stage. *Environ. Sci. Technol.* **52**, 5959–5967 (2018), doi:10.1021/acs.est.8b01197.

190. F. Piccinno, R. Hischier, S. Seeger, C. Som, Life Cycle Assessment of a New Technology To Extract, Functionalize and Orient Cellulose Nanofibers from Food Waste. *ACS Sustainable Chem. Eng.* **3**, 1047–1055 (2015), doi:10.1021/acssuschemeng.5b00209.

191. J. E. Winandy, J. J. Morrell, Improving the utility, performance, and durability of wood- and bio-based composites. *Ann. For. Sci.* **74**, 74 (2017), doi:10.1007/s13595-017-0625-2.

192. D. A. Dozier, *Materials Research in the FY 2016 Budget* (2015) (available at https://www.aaas.org/fy16budget/materials-research-fy-2016-budget).

193. P. Dewick, M. Miozzo, Sustainable technologies and the innovation–regulation paradox. *Futures*. **34**, 823–840 (2002), doi:10.1016/S0016-3287(02)00029-0.

194. D. S. Thorpe, Uptake of Advanced and Sustainable Engineering Materials in Civil Infrastructure Projects. *International Journal of Geomate*. **8**, 1180–1185 (2015), doi:10.21660/2015.15.4239.

195. P. Davis, T. Gajendran, J. Vaughan, T. Owi, Assessing construction innovation. *Constr. Econ. Build.* **16**, 104 (2016), doi:10.5130/AJCEB.v16i3.5178.

196. P. O. Akadiri, Understanding barriers affecting the selection of sustainable materials in building projects. *J. Build. Eng.* **4**, 86–93 (2015), doi:10.1016/j.jobe.2015.08.006.

197. W. R. Bitman, N. Sharif, A Conceptual Framework for Ranking R&D Projects. *IEEE Trans. Eng. Manage.* **55**, 267–278 (2008), doi:10.1109/TEM.2008.919725.

198. J. V. Kovach, D. Ingle, An approach for identifying and selecting improvement projects. *Total Quality Management & Business Excellence*. **38**, 1–12 (2018), doi:10.1080/14783363.2017.1419055.

199. L. D. Phillips, C. A. Bana e Costa, Transparent prioritisation, budgeting and resource allocation with multi-criteria decision analysis and decision conferencing. *Annals of Operations Research*. **154**, 51–68 (2007), doi:10.1007/s10479-007-0183-3.

200. R. Kolisch, K. Meyer, R. Mohr, Maximizing R&D Portfolio Value. *Research-Technology Management*. **48**, 33–39 (2015), doi:10.1080/08956308.2005.11657313.

201. D. Vagiona, Environmental performance value of projects. *Int. J. Sustainable Development and Planning*. **10**, 315–330 (2015), doi:10.2495/SDP-V10-N3-315-330.

202. B. Stosic, R. Milutinovic, N. Zakic, N. Zivkovic, Selected indicators for evaluation of eco-innovation projects. *Innovation: The European Journal of Social Science Research*. **29**, 177–191 (2016), doi:10.1080/13511610.2016.1157682.

203. P. O. Akadiri, P. O. Olomolaiye, E. A. Chinyio, Multi-criteria evaluation model for the selection of sustainable materials for building projects. *Automation in Construction*. **30**, 113–125 (2013), doi:10.1016/j.autcon.2012.10.004.

204. K. Govindan, K. Madan Shankar, D. Kannan, Sustainable material selection for construction industry – A hybrid multi criteria decision making approach. *Renewable Sustainable Energy Rev.* **55**, 1274–1288 (2016), doi:10.1016/j.rser.2015.07.100.

205. S. M. Khoshnava, R. Rostami, A. Valipour, M. Ismail, A. R. Rahmat, Rank of green building material criteria based on the three pillars of sustainability using the hybrid multi criteria decision making method. *J. Cleaner Prod.* **173**, 82–99 (2018), doi:10.1016/j.jclepro.2016.10.066.

206. A. Takano, M. Hughes, S. Winter, A multidisciplinary approach to sustainable building material selection. *Building and Environment*. **82**, 526–535 (2014), doi:10.1016/j.buildenv.2014.09.026.

207. W. Wang, R. Zmeureanu, H. Rivard, Applying multi-objective genetic algorithms in green building design optimization. *Building and Environment*. **40**, 1512–1525 (2005), doi:10.1016/j.buildenv.2004.11.017.

208. J. M. Allwood, M. F. Ashby, T. G. Gutowski, E. Worrell, Material efficiency. *Resour., Conserv. Recycl*. **55**, 362–381 (2011), doi:10.1016/j.resconrec.2010.11.002.

209. B. J. Skinner, Earth resources. *PNAS*. **76**, 4212–4217 (1979).

210. F. Pacheco-Torgal, J. A. Labrincha, The future of construction materials research and the seventh UN Millennium Development Goal. *Constr. Build. Mater.* **40**, 729–737 (2013), doi:10.1016/j.conbuildmat.2012.11.007.

211. M. F. Ashby, Y.J.M. Bréchet, D. Cebon, L. Salvo, Selection strategies for materials and processes. *Mater. Des.* **25**, 51–67 (2004), doi:10.1016/S0261-3069(03)00159-6.

212. M. F. Ashby, *Materials Selection in Mechanical Design* (Butterworth-Heinemann, Burlington, MA, ed. 5, 2016).

213. E. S. Bakhoum, D. C. Brown, A hybrid approach using AHP–TOPSIS–entropy methods for sustainable ranking of structural materials. *Int. J. Sust. Eng.* **6**, 212–224 (2013), doi:10.1080/19397038.2012.719553.

214. M.L.M. Broeren *et al.*, Early-stage sustainability assessment to assist with material selection. *J. Cleaner Prod.* **135**, 30–41 (2016), doi:10.1016/j.jclepro.2016.05.159.

215. J. W.K. Chan, T. K.L. Tong, Multi-criteria material selections and end-of-life product strategy. *Mater. Des.* **28**, 1539–1546 (2007), doi:10.1016/j.matdes.2006.02.016.

216. P. Chatterjee, V. M. Athawale, S. Chakraborty, Selection of materials using compromise ranking and outranking methods. *Mater. Des.* **30**, 4043–4053 (2009), doi:10.1016/j.matdes.2009.05.016.

217. A. Jahan, K. L. Edwards, M. Bahraminasab, *Multi-criteria decision analysis for supporting the selection of engineering materials in product design* (Butterworth-Heinemann, Amsterdam, ed. 2, 2016).

218. D. Jato-Espino, E. Castillo-Lopez, J. Rodriguez-Hernandez, J. C. Canteras-Jordana, A review of application of multi-criteria decision making methods in construction. *Automation in Construction*. **45**, 151–162 (2014), doi:10.1016/j.autcon.2014.05.013.

219. D.-H. Jee, K.-J. Kang, A method for optimal material selection aided with decision making theory. *Mater. Des.* **21**, 199–206 (2000), doi:10.1016/S0261-3069(99)00066-7.

220. F. Piccinno *et al.*, Multi-perspective application selection. *J. Cleaner Prod.* **112**, 1199–1210 (2016), doi:10.1016/j.jclepro.2015.06.105.

221. R. V. Rao, A decision making methodology for material selection using an improved compromise ranking method. *Mater. Des.* **29**, 1949–1954 (2008), doi:10.1016/j.matdes.2008.04.019.

222. R. Sarfaraz Khabbaz, B. Dehghan Manshadi, A. Abedian, R. Mahmudi, A simplified fuzzy logic approach for materials selection in mechanical engineering design. *Mater. Des.* **30**, 687–697 (2009), doi:10.1016/j.matdes.2008.05.026.

223. A. Thakker, J. Jarvis, M. Buggy, A. Sahed, A novel approach to materials selection strategy case study. *Mater. Des.* **29**, 1973–1980 (2008), doi:10.1016/j.matdes.2008.04.022.

224. C.-C. Zhou, G.-F. Yin, X.-B. Hu, Multi-objective optimization of material selection for sustainable products. *Mater. Des.* **30**, 1209–1215 (2009), doi:10.1016/j.matdes.2008.06.006.

225. T. E. Graedel *et al.,* Methodology of metal criticality determination. *Environ. Sci. Technol.* **46**, 1063–1070 (2012), doi:10.1021/es203534z.

226. T. E. Graedel, E. M. Harper, N. T. Nassar, P. Nuss, B. K. Reck, Criticality of metals and metalloids. *PNAS*. **112**, 4257–4262 (2015), doi:10.1073/pnas.1500415112.

227. D. Rosenau-Tornow, P. Buchholz, A. Riemann, M. Wagner, Assessing the long-term supply risks for mineral raw materials—a combined evaluation of past and future trends. *Resour. Policy*. **34**, 161–175 (2009), doi:10.1016/j.resourpol.2009.07.001.

228. L. Erdmann, T. E. Graedel, Criticality of non-fuel minerals. *Environ. Sci. Technol.* **45**, 7620–7630 (2011), doi:10.1021/es200563g.

229. S. Lloyd, J. Lee, A. Clifton, L. Elghali, C. France, Recommendations for assessing materials criticality. *Proc. Inst. Civ. Eng.: Waste Resour. Manage.* **165**, 191–200 (2012), doi:10.1680/warm.12.00002.

230. R. W. Scholz, F.-W. Wellmer, Approaching a dynamic view on the availability of mineral resources. *Global Environmental Change*. **23**, 11–27 (2013), doi:10.1016/j.gloenvcha.2012.10.013.

231. B. Hou *et al.,* The cost of corrosion in China. *npj Mater Degrad*. **1**, 29 (2017), doi:10.1038/s41529-017-0005-2.

232. U.M. Angst, B. Elsener, in *Concrete solutions: Proceedings of Concrete Solutions, 6th International Conference on Concrete Repair, Thessaloniki, Greece, 20-23 June 2016,* M. Grantham, Ed. (CRC Press, Boca Raton, 2016), pp. 391–396.

233. K. L. Scrivener, V. M. John, E. M. Gartner, “Eco-efficient cements: Potential, economically viable solutions for a low-CO2, cement-based materials industry”. (United Nations Environmental Program, 2016).

234. T. Liengen, R. Basseguy, D. Feron, I. Beech, Eds., *Understanding biocorrosion, Fundamentals and applications* (Woodhead Publishing, Amsterdam, ed. 1, 2014).

235. M. Holmgren, T. Svensson, E. Johnson, K. Johansson, Reflections regarding uncertainty of measurement, on the results of a Nordic fatigue test interlaboratory comparison. *Accred Qual Assur*. **10**, 208–213 (2005), doi:10.1007/s00769-005-0910-x.

236. P. Ghisellini, M. Ripa, S. Ulgiati, Exploring environmental and economic costs and benefits of a circular economy approach to the construction and demolition sector. A literature review. *J. Cleaner Prod.* **178**, 618–643 (2018), doi:10.1016/j.jclepro.2017.11.207.

237. J. R. Correia, Y. Bai, T. Keller, A review of the fire behaviour of pultruded GFRP structural profiles for civil engineering applications. *Compos. Struct.* **127**, 267–287 (2015), doi:10.1016/j.compstruct.2015.03.006.

238. European Commission, "Decision of 8 Feburary 2000 implementing Council Directive 89/106/EEC as regards the classification of the reaction to fire performance of construction products". (2006).

239. ASTM International, *Test Methods for Fire Tests of Building Construction and Materials* (ASTM International, West Conshohocken, PA, 2016).

240. T. Aidt, L. Jia, H. Low, Are prices enough? The economics of material demand reduction. *Philos. Trans. R. Soc., A*. **375** (2017), doi:10.1098/rsta.2016.0370.

241. European Commission, « EU Construction & Demolition Waste Management Protocol ». (2016).

242. Pré Consultants B.V., *SimaPro, the world's leading LCA software* (available at https://simapro.com/).

243. M. Goedkoop *et al.*, "ReCiPe 2008, A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level". (Ministerie van VROM, 2013).

244. R. B. Gordon, M. Bertram, T. E. Graedel, On the sustainability of metal supplies. *Resour. Policy*. **32**, 24–28 (2007), doi:10.1016/j.resourpol.2007.04.002.

245. J. E. Tilton, G. Lagos, Assessing the long-run availability of copper. *Resour. Policy*. **32**, 19–23 (2007), doi:10.1016/j.resourpol.2007.04.001.

246. U.S. Geological Survey, "Mineral Commodity Summaries 2017". (U.S. Geological Survey, 2017;https://doi.org/10.3133/70180197).

247. S. A. Rhoades, The herfindahl-hirschman index. *Fed. Res. Bull.* **79**, 188 (1993).

248. U.S. Department of Justice, "Horizontal Merger Guidelines". (U.S. Department of Justice, 2010).

249. M. E. Porter, How competitive forces shape strategy. *Harvard Business Review*. **57**, 137–145 (1979).

250. S. Frijia, S. Guhathakurta, E. Williams, Functional unit, technological dynamics, and scaling properties for the life cycle energy of residences. *Environmental science & technology*. **46**, 1782–1788 (2012), doi:10.1021/es202202q.

251. R. L. Reuben, *Materials in Marine Technology* (Springer London, London, 1994).

252. P. L. J. Domone, J. M. Illston, *Construction materials, Their nature and behaviour / edited by Peter Domone and John Illston* (Spon Press, London, New York, ed. 4, 2010).

253. S. C. Dexter, *Handbook of oceanographic engineering materials* (Wiley, New York, Chichester, 1979).

254. S. Kalpakjian, S. R. Schmid, *Manufacturing engineering and technology* (Pearson, Upper Saddle River NJ, 2014).

255. D. V. Reddy, A. S. J. Swamidas, *Essentials of Offshore Structures, Framed and Gravity Platforms* (CRC Press, Hoboken, 2013).

256. B. Valdez *et al.*, Corrosion assessment of infrastructure assets in coastal seas. *Journal of Marine Engineering & Technology*. **15**, 124–134 (2016), doi:10.1080/20464177.2016.1247635.

257. T. E. Norgate, S. Jahanshahi, W. J. Rankin, Assessing the environmental impact of metal production processes. *Journal of Cleaner Production*. **15**, 838–848 (2007), doi:10.1016/j.jclepro.2006.06.018.

258. N.R. Baddoo, B.A. Burgan, "Structural Design of Stainless Steel". (The Steel Construction Institute, 2001;http://www.bssa.org.uk/cms/File/SCI%20291%20Structural%20Design%20of%20Stainless%20Steel.pdf).

259. J. R. Davis, *Alloying*, *Understanding the basics / edited by J.R. Davis, Davis & Associates* (ASM International, Materials Park, Ohio, 2001).

260. Titanex GmbH, *Titanium Grade 5 / 23 / ELI* (available at http://shop.titanex.com/PDFs/Grade_5_23_ELI.pdf).

261. H. Fang, Y. Bai, W. Liu, Y. Qi, J. Wang, Connections and structural applications of fibre reinforced polymer composites for civil infrastructure in aggressive environments. *Composites Part B: Engineering*. **164**, 129–143 (2019), doi:10.1016/j.compositesb.2018.11.047.

262. M. A. Shahawy, M. Arockiasamy, T. Beitelman, R. Sowrirajan, Reinforced concrete rectangular beams strengthened with CFRP laminates. *Composites Part B: Engineering*. **27B**, 225–233 (1996).

263. T. Uomoto, H. Mutsuyoshi, F. Katsuki, S. Misra, Use of fiber reinforced polymer composites as reinforcing material for concrete. *Journal of Materials in Civil Engineering*. **14**, 191–209 (2002).

264. J. Bai, Ed., *Advanced fibre-reinforced polymer (frp) composites for structural applications* (Woodhead Pub, Philadelphia PA, 2013).

265. J. Graham-Jones, J. Summerscales, *Marine applications of advanced fibre-reinforced composites* (Woodhead Publishing, Oxford, 2015).

266. M. Berges *et al.*, Influence of moisture uptake on the static, cyclic and dynamic behaviour of unidirectional flax fibre-reinforced epoxy laminates. *Composites Part A: Applied Science and Manufacturing*. **88**, 165–177 (2016), doi:10.1016/j.compositesa.2016.05.029.
267. J. R. Correia *et al.*, Durability of pultruded glass-fiber-reinforced polyester profiles for structural applications. *Mechanics of Composite Materials*. **42**, 325–338 (2006), doi:10.1007/s11029-006-0042-3.
268. J. D. Garcia-Espinel, D. Castro-Fresno, P. Parbole Gayo, F. Ballester-Muñoz, Effects of sea water environment on glass fiber reinforced plastic materials used for marine civil engineering constructions. *Materials & Design (1980-2015)*. **66**, 46–50 (2015), doi:10.1016/j.matdes.2014.10.032.
269. A. Kootsookos, A. P. Mouritz, Seawater durability of glass- and carbon-polymer composites. *Composites Science and Technology*. **64**, 1503–1511 (2004), doi:10.1016/j.compscitech.2003.10.019.
270. Q. Liu, M. T. Shaw, R. S. Parnas, A.-M. McDonnell, Investigation of basalt fiber composite aging behavior for applications in transportation. *Polym. Compos.* **27**, 475–483 (2006), doi:10.1002/pc.20215.
271. B. Wei, H. Cao, S. Song, Degradation of basalt fibre and glass fibre/epoxy resin composites in seawater. *Corrosion Science*. **53**, 426–431 (2011), doi:10.1016/j.corsci.2010.09.053.
272. M. Frigione, M. Lettieri, Durability Issues and Challenges for Material Advancements in FRP Employed in the Construction Industry. *Polymers*. **10** (2018), doi:10.3390/polym10030247.
273. K. L. Pickering, M. A. Efendy, T. M. Le, A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A: Applied Science and Manufacturing*. **83**, 98–112 (2016), doi:10.1016/j.compositesa.2015.08.038.
274. C. Colombo, L. Vergani, M. Burman, Static and fatigue characterisation of new basalt fibre reinforced composites. *Composite Structures*. **94**, 1165–1174 (2012), doi:10.1016/j.compstruct.2011.10.007.
275. V. Fiore, T. Scalici, G. Di Bella, A. Valenza, A review on basalt fibre and its composites. *Composites Part B: Engineering*. **74**, 74–94 (2015), doi:10.1016/j.compositesb.2014.12.034.
276. International Energy Agency, Cement Sustainability Initiative, "Technology Roadmap - Low-Carbon Transition in the Cement Industry". (2018).

277. R. J. Flatt, N. Roussel, C. R. Cheeseman, Concrete: An eco material that needs to be improved. *Journal of the European Ceramic Society*. **32**, 2787–2798 (2012), doi:10.1016/j.jeurceramsoc.2011.11.012.

278. J. L. Provis, Alkali-activated materials. *Cement and Concrete Research*. **114**, 40–48 (2017), doi:10.1016/j.cemconres.2017.02.009.

279. E. Gartner, T. Sui, Alternative cement clinkers. *Cement and Concrete Research*. **114**, 27–39 (2018), doi:10.1016/j.cemconres.2017.02.002.

280. T. Hanein, J.-L. Galvez-Martos, M. N. Bannerman, Carbon footprint of calcium sulfoaluminate clinker production. *Journal of Cleaner Production*. **172**, 2278–2287 (2018), doi:10.1016/j.jclepro.2017.11.183.

281. J. L. Provis, J. S. J. van Deventer, *Alkali activated materials, State-of-the-art report, RILEM TC 224-AAM / John L. Provis, Jannie S.J. van Deventer, editors* (Springer, Dordrecht, 2014).

282. K. Arbi, M. Nedeljković, Y. Zuo, G. Ye, A Review on the Durability of Alkali-Activated Fly Ash/Slag Systems. *Ind. Eng. Chem. Res.* **55**, 5439–5453 (2016), doi:10.1021/acs.iecr.6b00559.

283. G. Markeset, S. Rostam, O. Klinghoffer, *Guide for the use of stainless steel reinforcement in concrete structures* (Byggforsk, Oslo, 2006).

284. S. W. Tang, Y. Yao, C. Andrade, Z. J. Li, Recent durability studies on concrete structure. *Cement and Concrete Research*. **78**, 143–154 (2015), doi:10.1016/j.cemconres.2015.05.021.

285. D. V. Reddy, J.-B. Edouard, K. Sobhan, S. S. Rajpathak, in *Proceedings of the 36th Conference on Our World in Concrete & Structures, 14 - 16 August 2011, Singapore ; [conference documentation] volume XXX*, C. T. Tam, Ed. (CI-Premier Pte. Ltd, Singapore, 2011).

286. P. S. Matheu, K. Ellis, B. Varela, Comparing the Environmental Impacts of Alkali Activated Mortar and Traditional Portland Cement Mortar using Life Cycle Assessment. *IOP Conf. Ser.: Mater. Sci. Eng.* **96**, 12080 (2015), doi:10.1088/1757-899X/96/1/012080.

287. J.-P. Won, C.-G. Park, Effect of Environmental Exposure on the Mechanical and Bonding Properties of Hybrid FRP Reinforcing Bars for Concrete Structures. *Journal of Composite Materials*. **40**, 1063–1076 (2006), doi:10.1177/0021998305057362.

288. M. Olivia, P. K. Sarker, H. Nikraz, Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete. *Proceedings ICCBT2008 - A - 46*, 5178–5530 (2008).

289. Italcementi Group, “ALIPRE - ALICEM, Environmental Product Declaration”. (2012).

290. Concrete Centre, *European standards for reinforcement* (available at http://www.concretecentre.com/Concrete-Design/Materials/European-standards-for-reinforcement.aspx).

291. ACI Committee 440, 440.1R-06 Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars (2006).

292. M. H. Ramage *et al.*, The wood from the trees. *Renewable and Sustainable Energy Reviews*. **68**, 333–359 (2017), doi:10.1016/j.rser.2016.09.107.

293. O. Espinoza, U. Buehlmann, Cross-Laminated Timber in the USA: Opportunity for Hardwoods? *Curr Forestry Rep*. **4**, 1–12 (2018), doi:10.1007/s40725-018-0071-x.

294. T. Singh, D. Page, I. Simpson, Manufactured structural timber building materials and their durability. *Construction and Building Materials*. **217**, 84–92 (2019), doi:10.1016/j.conbuildmat.2019.05.036.

295. K. Gradeci, N. Labonnote, B. Time, J. Köhler, Mould growth criteria and design avoidance approaches in wood-based materials – A systematic review. *Construction and Building Materials*. **150**, 77–88 (2017), doi:10.1016/j.conbuildmat.2017.05.204.

296. Granta Material Intelligence, *MaterialUniverse materials data* (2018) (available at http://www.grantadesign.com/products/data/materialuniverse.htm).

297. C. P. De, Use of titanium and its alloys in sea-water service. *High Temperature Materials and Processes*. **11**, 61–96 (1993).

298. D. Krouse, N. Laycock, C. Padovani, Modelling pitting corrosion of stainless steel in atmospheric exposures to chloride containing environments. *Corrosion Engineering, Science and Technology*. **49**, 521–528 (2014), doi:10.1179/1743278214Y.0000000221.

299. R. H. Jones, *Stress-corrosion cracking, Materials performance and evaluation / edited by Russell H. Jones* (ASM International, Materials Park, 2017).

300. T. Moan, Life-cycle assessment of marine civil engineering structures. *Structure and Infrastructure Engineering*. **7**, 11–32 (2011), doi:10.1080/15732471003588254.

301. S.-m. Sŏng, O. Younossi, B. W. Goldsmith, *Titanium, Industrial base, price trends, and technology initiatives* (RAND Project Air Force, Santa Monica, CA, 2009).

302. World Bank, “World Bank Commodities Price Forecast 2017”. (2017).

303. M. Hope, “Mineral Sand Forecasts”. (Credite Suisse, 2017).

304. Ametek, “Master Alloys and Titanium Raw Materials - The Dog Wagging the Tail”. (2017).

305. T. Perles, “Vanadium Market Outlook”. (TTP Squared, 2013).

306. ASD Reports, *Duplex Stainless Steel Market - Global Forecast to 2021* (2017) (available at https://www.asdreports.com/market-research-report-372979/duplex-stainless-steel-market-global-forecast).

307. UNEP – International Resource Panel, “Recycling Rates of Metals – A Status Report”. (United Nations Environmental Program, 2011).

308. J. Bowyer *et al., “*Understanding Steel Recovery and Recycling Rates and Limitations to Recycling”. (Dovetail Partners Inc., 2015).

309. I. J. Polmear, D. St. John, J.-F. Nie, M. Qian, *Light alloys*, *Metallurgy of the light metals* (Butterworth-Heinemann, Amsterdam, 2017).

310. G. Liu, C. E. Bangs, D. B. Müller, Stock dynamics and emission pathways of the global aluminium cycle. *Nature Clim Change*. **3**, 338–342 (2013), doi:10.1038/nclimate1698.

311. J. Morfeldt, W. Nijs, S. Silveira, “The Future of Global Steel Production”. (KTH Royal Institute of Technology, 2013;http://www.internationalenergywork-shop.org/docs/IEW%202013_3A2Morfeldt.pdf).

312. OECD, “Steel raw materials, DSTI/SU/SC(2011)2, 70th Steel Committee Meeting”. (2011).

313. World Steel Association, “Global steel industry: outlook, challenges and opportunities”. (World Steel Association, 2017).

314. Glencore, “Nickel Market Developments”. (2016).

315. M. Selby, “Nickel Production and Supply: Market Implications”. (RNC Minerals, 2017).

316. F. Pothen, T. Goeschl, A. Löschel, “Strategic Trade Policy and Critical Raw Materials in Stainless Steel Production”. (Zetrum für Europäische Wirtschaftsforschung GmbH, 2013).

317. R. Kleijn, E. van der Voet, G. J. Kramer, L. van Oers, C. van der Giesen, Metal requirements of low-carbon power generation. *Energy*. **36**, 5640–5648 (2011), doi:10.1016/j.energy.2011.07.003.

318. R. Flook, “Bauxite & Alumina 2015 - Non-metallurgical market review”. (Mosman Resources, 2015;https://www.metalbulletin.com/events/download.ashx/document/speaker/8449/a0ID000000X0j5LMAR/Presentation).

319. K. Fog, “Hydro - Capital Markets Day 2016 - Market Outlook”. (Hydro, 2016).

320. D. McCoy, “Titanium Minerals Market”. (TZ Minerals International Pty Ltd, 2017).

321. S. Gehler, “World Titanium Sponge Supply Situation”. (UKTMP, 2017).

322. T. Hohne-Sparboth, “An outlook for titanium metal”. (Roskill, 2017).

323. Verkhnaya Salda Metallurgical Production Association, “Titanium Raw Materials in Russia and Around the World”. (2006).

324. M. Mistry, Nickel: Creating Sustainability in the Long Term, Berlin, 13 November 2012.

325. BP, “BP Statistical Review of World Energy 2018”. (2018).

326. M. F. Montemor, Functional and smart coatings for corrosion protection: A review of recent advances. *Surface and Coatings Technology*. **258**, 17–37 (2014), doi:10.1016/j.surfcoat.2014.06.031.

327. B. Zhou, Z. Li, C. Chen, Global Potential of Rare Earth Resources and Rare Earth Demand from Clean Technologies. *Minerals*. **7**, 203 (2017), doi:10.3390/min7110203.

328. V. Koehlé-Divo *et al.*, Genotoxicity and physiological effects of CeO2 NPs on a freshwater bivalve (Corbicula fluminea). *Aquatic toxicology (Amsterdam, Netherlands)*. **198**, 141–148 (2018), doi:10.1016/j.aquatox.2018.02.020.

329. M. Sendra, J. Blasco, C. V.M. Araújo, Is the cell wall of marine phytoplankton a protective barrier or a nanoparticle interaction site? Toxicological responses of Chlorella autotrophica and Dunaliella salina to Ag and CeO2 nanoparticles. *Ecological Indicators*. **95**, 1053–1067 (2018), doi:10.1016/j.ecolind.2017.08.050.

330. A. W. Momber, P. Plagemann, V. Stenzel, Performance and integrity of protective coating systems for offshore wind power structures after three years under offshore site conditions. *Renewable Energy*. **74**, 606–617 (2015), doi:10.1016/j.renene.2014.08.047.

331. A. López-Ortega, R. Bayón, J. L. Arana, Evaluation of protective coatings for offshore applications. Corrosion and tribocorrosion behavior in synthetic seawater. *Surface and Coatings Technology*. **349**, 1083–1097 (2018), doi:10.1016/j.surfcoat.2018.06.089.

332. L. A. Golding *et al.*, Derivation of a water quality guideline for aluminium in marine waters. *Environmental toxicology and chemistry*. **34**, 141–151 (2015), doi:10.1002/etc.2771.

333. T. Kirchgeorg *et al.*, Emissions from corrosion protection systems of offshore wind farms: Evaluation of the potential impact on the marine environment. *Marine pollution bulletin*. **136**, 257–268 (2018), doi:10.1016/j.marpolbul.2018.08.058.

334. S. K. Behera, A. F. Mulaba-Bafubiandi, Microbes Assisted Mineral Flotation a Future Prospective for Mineral Processing Industries: A Review. *Mineral Processing and Extractive Metallurgy Review*. **38**, 96–105 (2017), doi:10.1080/08827508.2016.1262861.

335. T. Hidalgo, L. Kuhar, A. Beinlich, A. Putnis, Kinetic study of chalcopyrite dissolution with iron(III) chloride in methanesulfonic acid. *Minerals Engineering*. **125**, 66–74 (2018), doi:10.1016/j.mineng.2018.05.025.

336. O. Laitinen *et al.*, Alkyl aminated nanocelluloses in selective flotation of aluminium oxide and quartz. *Chemical Engineering Science*. **144**, 260–266 (2016), doi:10.1016/j.ces.2016.01.052.

337. T. Norgate, S. Jahanshahi, Reducing the greenhouse gas footprint of primary metal production: Where should the focus be? *Minerals Engineering*. **24**, 1563–1570 (2011), doi:10.1016/j.mineng.2011.08.007.

338. S. Capuzzi, G. Timelli, Preparation and Melting of Scrap in Aluminum Recycling: A Review. *Metals*. **8**, 249 (2018), doi:10.3390/met8040249.

339. S. Nakamura, Y. Kondo, K. Nakajima, H. Ohno, S. Pauliuk, Quantifying Recycling and Losses of Cr and Ni in Steel Throughout Multiple Life Cycles Using MaTrace-Alloy. *Environmental science & technology*. **51**, 9469–9476 (2017), doi:10.1021/acs.est.7b01683.

340. L. Reijnders, Conserving functionality of relatively rare metals associated with steel life cycles: a review. *Journal of Cleaner Production*. **131**, 76–96 (2016), doi:10.1016/j.jclepro.2016.05.073.

341. O. Takeda, T. H. Okabe, Current Status of Titanium Recycling and Related Technologies. *JOM*. **78**, 1 (2018), doi:10.1007/s11837-018-3278-1.

342. K. Nakajima *et al.*, Bottlenecks in material cycle of nickel. *Matériaux & Techniques*. **104**, 604 (2016), doi:10.1051/mattech/2017011.

343. M. Cesetti, P. Nicolosi, Waste processing: new near infrared technologies for material identification and selection. *J. Inst.* **11**, C09002-C09002 (2016), doi:10.1088/1748-0221/11/09/C09002.

344. X. Lu, K. Matsubae, K. Nakajima, S. Nakamura, T. Nagasaka, Thermodynamic Considerations of Contamination by Alloying Elements of Remelted End-of-Life Nickel- and Cobalt-Based Superalloys. *Metall and Materi Trans B*. **47**, 1785–1795 (2016), doi:10.1007/s11663-016-0665-2.

345. H. Ohno *et al.*, Optimal Recycling of Steel Scrap and Alloying Elements: Input-Output based Linear Programming Method with Its Application to End-of-Life Vehicles in Japan. *Environmental science & technology*. **51**, 13086–13094 (2017), doi:10.1021/acs.est.7b04477.

346. Z. Z. Fang, S. Middlemas, J. Guo, P. Fan, A new, energy-efficient chemical pathway for extracting Ti metal from Ti minerals. *Journal of the American Chemical Society*. **135**, 18248–18251 (2013), doi:10.1021/ja408118x.

347. B.-M. Moon *et al.*, Method of recycling titanium scraps via the electromagnetic cold crucible technique coupled with calcium treatment. *Journal of Alloys and Compounds*. **727**, 931–939 (2017), doi:10.1016/j.jallcom.2017.08.129.

348. Y.-k. Taninouchi, Y. Hamanaka, T. H. Okabe, Chlorination-Volatilization Behavior of Titanium Metal Scraps during Recycling Using Reaction-Mediating Molten Salt. *Mater. Trans.* **57**, 1309–1318 (2016), doi:10.2320/matertrans.M-M2016818.

349. T. H. Okabe, Y.-k. Taninouchi, in *Advances in Molten Slags, Fluxes, and Salts, Proceedings of the 10th International Conference on Molten Slags, Fluxes, and Salts 2016*, P.

Chaubal, R. Reddy, P. C. Pistorius, U. Pal, Eds. (Springer International Publishing, Cham, 2016), vol. **78,** pp. 751–760.

350. J. Reitz, C. Lochbichler, B. Friedrich, Recycling of gamma titanium aluminide scrap from investment casting operations. *Intermetallics*. **19**, 762–768 (2011), doi:10.1016/j.intermet.2010.11.015.
351. J. Kang, T. H. Okabe, Removal of iron from titanium ore by selective chlorination using TiCl4 under high oxygen chemical potential. *International Journal of Mineral Processing*. **149**, 111–118 (2016), doi:10.1016/j.minpro.2016.02.014.
352. N. Kulkarni, H. Mahfuz, S. Jeelani, L. A. Carlsson, Fatigue crack growth and life prediction of foam core sandwich composites under flexural loading. *Composite Structures*. **59**, 499–505 (2003).
353. V. M. Karbhari, Ed., *Durability of composites for civil structural applications* (Woodhead, Cambridge, 2007).
354. L. Yan, N. Chouw, K. Jayaraman, Effect of UV and water spraying on the mechanical properties of flax fabric reinforced polymer composites used for civil engineering applications. *Materials & Design*. **71**, 17–25 (2015), doi:10.1016/j.matdes.2015.01.003.
355. A. M. Figliolini, L. A. Carlsson, Mechanical properties of vinylester resins exposed to marine environments. *Polym Eng Sci*. **53**, 2413–2421 (2013), doi:10.1002/pen.23496.
356. A. M. Figliolini, L. A. Carlsson, Mechanical properties of carbon fiber/vinylester composites exposed to marine environments. *Polym. Compos.* **35**, 1559–1569 (2014), doi:10.1002/pc.22809.
357. M. Latif, M.N. Prabhakar, J. Song, Fabrication of hybrid matrix/silane modified carbon fabric composites and study of their mechanical properties. *J. Appl. Polym. Sci.* **136**, 47695 (2019), doi:10.1002/app.47695.
358. F. A. Ramirez, L. A. Carlsson, B. A. Acha, Evaluation of water degradation of vinylester and epoxy matrix composites by single fiber and composite tests. *J Mater Sci*. **43**, 5230–5242 (2008), doi:10.1007/s10853-008-2766-z.
359. L. Yan, N. Chouw, K. Jayaraman, Flax fibre and its composites – A review. *Composites Part B: Engineering*. **56**, 296–317 (2014), doi:10.1016/j.compositesb.2013.08.014.
360. C. Affolter, M. Barbezat, G. Piskoty, O. Neuner, G. Terrasi, Failure of a sag water pipe triggered by aging of the GFRP composite relining. *Engineering Failure Analysis*. **84**, 358–370 (2018), doi:10.1016/j.engfailanal.2017.09.017.
361. J. R. Correia, F. A. Branco, J. G. Ferreira, The effect of different passive fire protection systems on the fire reaction properties of GFRP pultruded profiles for civil construction.

Composites Part A: Applied Science and Manufacturing. **41**, 441–452 (2010), doi:10.1016/j.compositesa.2009.12.002.

362. T. Hertzberg, Dangers relating to fires in carbon-fibre based composite material. *Fire Mater.* **29**, 231–248 (2005), doi:10.1002/fam.882.
363. Q. Nguyen, T. Ngo, P. Mendis, P. Tran, Composite materials for next generation building façade systems. *Civil Engineering and Architecture*. **1**, 88–95 (2013).
364. H. Seefeldt, *Flame retardancy of wood-plastic composites*, Zugl.: Berlin, Techn. Univ., Diss., 2012 (Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, 2012).
365. A. M. Alhuthali, I.-M. Low, Effect of prolonged water absorption on mechanical properties in cellulose fiber reinforced vinyl-ester composites. *Polym Eng Sci*. **55**, 2685–2697 (2015), doi:10.1002/pen.23617.
366. V. Fiore *et al.*, Effects of aging in salt spray conditions on flax and flax/basalt reinforced composites: Wettability and dynamic mechanical properties. *Composites Part B: Engineering*. **93**, 35–42 (2016), doi:10.1016/j.compositesb.2016.02.057.
367. S. Job *et al.*, “Composites Recycling: Where are we now?”. (Composites UK, 2016;https://compositesuk.co.uk/system/files/documents/Recycling%20Report%202016.pdf).
368. G. Oliveux, L. O. Dandy, G. A. Leeke, Current status of recycling of fibre reinforced polymers. *Progress in Materials Science*. **72**, 61–99 (2015), doi:10.1016/j.pmatsci.2015.01.004.
369. A. W. van Vuure, J. Baets, K. Wouters, K. Hendrickx, Compressive properties of natural fibre composites. *Materials Letters*. **149**, 138–140 (2015), doi:10.1016/j.matlet.2015.01.158.
370. A. Le Duigou, P. Davies, C. Baley, Seawater ageing of flax/poly(lactic acid) biocomposites. *Polymer Degradation and Stability*. **94**, 1151–1162 (2009), doi:10.1016/j.polymdegradstab.2009.03.025.
371. T. Bhat, D. Fortomaris, E. Kandare, A. P. Mouritz, Properties of thermally recycled basalt fibres and basalt fibre composites. *Journal of Materials Science* (2017), doi:10.1007/s10853-017-1672-7.
372. S. Das, J. Warren, D. West, S. M. Schexnayder, “Global Carbon Fiber Composites Supply Chain Competitiveness Analysis”. (CleanEnergyManufacturingAnalysis Center, 2016;https://www.nrel.gov/docs/fy16osti/66071.pdf).
373. E. Witten, T. Kraus, M. Kühnel, “Composites Market Report 2016”. (AVK, CCeV, 2016).

374. Lucintel, *Opportunities in Natural Fiber Composites* (2011) (available at http://www.lucintel.com/lucintelbrief/potentialofnaturalfibercomposites-final.pdf).

375. Lucintel, *Emerging Innovation Trends in Composites* (2015) (available at https://www.easyfairs.com/fileadmin/groups/8/Advanced_Engineering/Advanced_Engineering_2016/AE_2015_presentations/Weds__forum_3_-_Nigel_O_Dea_-_Emerging_Innovations_in_Composites-Lucintel__UK_Adv_Eng_Show_15_N_ODea_ver_Final.pdf).

376. K. Azrague *et al.*, Life Cycle Assessment as a tool for resource optimisation of continuous basalt fibre production in Iceland. *Life Cycle Assessment and Other Assessment Tools for Waste Management and Resource Optimization* (2016).

377. Z. Sun, Progress in the research and applications of natural fiber-reinforced polymer matrix composites. *Science and Engineering of Composite Materials*. **25**, 835–846 (2018), doi:10.1515/secm-2016-0072.

378. Y. Wu, C. Xia, L. Cai, A. C. Garcia, S. Q. Shi, Development of natural fiber-reinforced composite with comparable mechanical properties and reduced energy consumption and environmental impacts for replacing automotive glass-fiber sheet molding compound. *Journal of Cleaner Production*. **184**, 92–100 (2018), doi:10.1016/j.jclepro.2018.02.257.

379. P. B. Bamforth, *Properties of concrete for use in Eurocode 2, How to optimise the engineering properties of concrete in design to Eurocode 2* (Concrete Center, Surrey, 2008).

380. Lafarge SA, *Aether - Lower Carbon Cements* (2014) (available at http://www.aether-cement.eu/results.html).

381. M. A. Sawpan, A. A. Mamun, P. G. Holdsworth, Long term durability of pultruded polymer composite rebar in concrete environment. *Materials & Design*. **57**, 616–624 (2014), doi:10.1016/j.matdes.2014.01.049.

382. G. Y. Koga, B. Albert, V. Roche, R. P. Nogueira, A comparative study of mild steel passivation embedded in Belite-Ye'elimite-Ferrite and Porland cement mortars. *Electrochimica Acta*. **261**, 66–77 (2018), doi:10.1016/j.electacta.2017.12.128.

383. C. Wang, G. Xian, J. Ou, Durability study of GFRP rebar in alkali, acid and salt solution. *American Concrete Institute, ACI Special Publication*. **2** (2011).

384. M. d. Engelhardt *et al.*, *in Structures Congress 2013, Bridging Your Profession with Your Passion*, B. J. Leshko, J. McHugh, Eds. (American Society of Civil Engineers, Reston, May 2013), pp. 1138–1149.

385. J. Provis, "Fire resistance of geopolymer concretes". (AOARD, 2010).

386. E. Annerel, L. Taerwe, Revealing the temperature history in concrete after fire exposure by microscopic analysis. *Cement and Concrete Research*. **39**, 1239–1249 (2009), doi:10.1016/j.cemconres.2009.08.017.

387. J. Kaufmann, F. Winnefeld, B. Lothenbach, Stability of ettringite in CSA cement at elevated temperatures. *Advances in Cement Research*. **28**, 251–261 (2016), doi:10.1680/jadcr.15.00029.

388. P. V. Krivenko, H. L. Cao, L. Q. Weng, O. N. Petropavlovskii, in *High Performance Concrete Technology and Applications*, S. Yilmaz, H. B. Ozmen, Eds. (InTech, 2016).

389. K. P. Verian, W. Ashraf, Y. Cao, Properties of recycled concrete aggregate and their influence in new concrete production. *Resources, Conservation and Recycling*. **133**, 30–49 (2018), doi:10.1016/j.resconrec.2018.02.005.

390. S. Lotfi, M. Eggimann, E. Wagner, R. Mróz, J. Deja, Performance of recycled aggregate concrete based on a new concrete recycling technology. *Construction and Building Materials*. **95**, 243–256 (2015), doi:10.1016/j.conbuildmat.2015.07.021.

391. S. Lotfi, P. Rem, Recycling of End of Life Concrete Fines into Hardened Cement and Clean Sand. *JEP*. **07**, 934–950 (2016), doi:10.4236/jep.2016.76083.

392. R. Jin, Q. Chen, Overview of Concrete Recycling Legislation and Practice in the United States. *J. Constr. Eng. Manage.* **145**, 5019004 (2019), doi:10.1061/(ASCE)CO.1943-7862.0001630.

393. M. del Río Merino, P. Izquierdo Gracia, I. S. Weis Azevedo, Sustainable construction. *Waste management & research*. **28**, 118–129 (2010).

394. F. Martirena, A. Favier, K. Scrivener, *Calcined clays for sustainable concrete, Proceedings of the 2nd international conference on calcined clays for sustainable concrete / Fernando Martirena, Aurélie Favier, Karen Scrivener, editors* (Springer, Dordrecht, The Netherlands, 2018).

395. LC3, *LC3 - Limestone Calcined Clay Cement* (2014) (available at https://www.lc3.ch/).

396. M. M. Hossain, M. R. Karim, M. K. Hossain, M. N. Islam, M.F.M. Zain, Durability of mortar and concrete containing alkali-activated binder with pozzolans: A review. *Construction and Building Materials*. **93**, 95–109 (2015), doi:10.1016/j.conbuildmat.2015.05.094.

397. T. Hanein *et al.*, Optimising calcium sulfoaluminate cements, University College London, 11 September 2017.

398. Forest Products Laboratory, *Wood Handbook, Wood as an Engineering Material // Understanding ecological impacts in rivers in England and Wales and identifying their possible causes* (Environment Agency, Almondsbury, 2008).

399. A.C. Oliver, *Timber for marine and freshwater construction* (Timber Research and Development Association, Hughenden Valley, High Wycombe, HP14 4ND Buckinghamshire, England, ed. 3, 1974).

400. F. Charles, J. Coston-Guarini, J.-M. Guarini, S. Fanfard, Wood decay at sea. *Journal of Sea Research*. **114**, 22–25 (2016), doi:10.1016/j.seares.2016.05.002.
401. M. Meaden, J. Williams, J. Simm, “Alternative hardwood timbers for use in marine and freshwater construction”. (Environment Agency, 2011;https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/291212/scho0411btpp-e-e.pdf).
402. R. Lopez-Anido, A. P. Michael, B. Goodell, T. C. Sandford, Assessment of Wood Pile Deterioration due to Marine Organisms. *Journal of Waterway, Port, Coastal, and Ocean Engineering*. **130**, 70–76 (2004), doi:10.1061/(ASCE)0733-950X(2004)130:2(70).
403. C. G. Björdal, Evaluation of microbial degradation of shipwrecks in the Baltic Sea. *International Biodeterioration & Biodegradation*. **70**, 126–140 (2012), doi:10.1016/j.ibiod.2012.01.012.
404. J. Y. Wang *et al.*, Durability of mass timber structures: a review of the biological risks. *Wood and Fiber Science*, 110–127 (2018).
405. Forest Products Laboratory, “Wood Handbook, Wood as an Engineering Material, General Technical Report FPL-GTR-190”. (United States Department of Agriculture, Forest Service, Forest Products Laboratory, April 2010).
406. Structural Timber Association, “Engineering Bulletin 7 - Fire Safety in Timber Buildings”. (Structural Timber Association, 2014).
407. A. I. Bartlett, R. M. Hadden, L. A. Bisby, A Review of Factors Affecting the Burning Behaviour of Wood for Application to Tall Timber Construction. *Fire Technol*. **55**, 1–49 (2019), doi:10.1007/s10694-018-0787-y.
408. J. Schmid, A. Just, M. Klippel, M. Fragiacomo, The Reduced Cross-Section Method for Evaluation of the Fire Resistance of Timber Members: Discussion and Determination of the Zero-Strength Layer. *Fire Technology*. **51**, 1285–1309 (2015), doi:10.1007/s10694-014-0421-6.
409. E. L. Schaffer, C. M. Marx, D. A. Bender, F. E. Woeste, Strength validation and fire endurance of glued-laminated timber beams. *(Research paper FPL; 467): 16 p.: ill.; 28 cm.* **467** (1986).
410. M. Crossman, J. Simm, *Manual on the Use of Timber in Coastal and River Engineering* (Thomas Telford Ltd, London, 2004).
411. M. Bumgardner, S. Johnson, W. Luppold, F. Maplesden, E. Pepke, in *The global forest sector, Changes, practices, and prospects*, E. Hansen, R. Panwar, R. P. Vlosky, Eds. (Taylor & Francis, Boca Raton, 2013), pp. 41–76.

412. FIM, “Global Timber Outlook”. (FIM Services Limited, 2015;https://darkroom.fim-ltd.co.uk/original/09fd8a5ed124902f8d87871096be5727:c1f739de890cc03662902a1e55b7b0fb).

413. T. Koellner *et al.*, Principles for life cycle inventories of land use on a global scale. *Int J Life Cycle Assess*. **18**, 1203–1215 (2013), doi:10.1007/s11367-012-0392-0.

414. F. Dinkel, C. Stettler, F. Werner, “Life Cycle Inventories of Renewable Materials, Final report ecoinvent data v2.0 No. 21”. (EMPA, Swiss Center for Life Cycle Inventories, 2007; ecoinvent.org).

415. Food and Agriculture Organization of the United Nations, “Global Forest Resources Assessment 2015. How are the World’s Forests Changing?”. (Food and Agriculture Organization of the United Nations, 2016).

416. F. Achard *et al.*, Determination of tropical deforestation rates and related carbon losses from 1990 to 2010. *Global change biology*. **20**, 2540–2554 (2014), doi:10.1111/gcb.12605.

417. ITTO, “Biennial review and assessment of the world timber situation 2015-2016”. (International Tropical Timber Organisation, 2017).

418. *State of the world’s forests 2016*, *Forests and agriculture : land-use challenges and opportunities* (Food and Agriculture Organization of the United Nations, Rome, 2016).

419. Union of Concerned Scientists, “Planting for the Future, How Demand for Wood Products Could Be Friendly to Tropical Forests”. (2014).

420. M. Castellote, C. Alonso, C. Andrade, X. Turrillas, J. Campo, Composition and microstructural changes of cement pastes upon heating, as studied by neutron diffraction. *Cement and Concrete Research*. **34**, 1633–1644 (2004), doi:10.1016/S0008-8846(03)00229-1.

421. World Business Council for Sustainable Development, “The Cement Sustainability Initiative, Recycling Concrete”. (World Business Council for Sustainable Development, 2009).

422. M. Dale, B. A. Acha, L. A. Carlsson, Low velocity impact and compression after impact characterization of woven carbon/vinylester at dry and water saturated conditions. *Composite Structures*. **94**, 1582–1589 (2012), doi:10.1016/j.compstruct.2011.12.025.

423. A. Afshar, H.-T. Liao, F.-p. Chiang, C. S. Korach, Time-dependent changes in mechanical properties of carbon fiber vinyl ester composites exposed to marine environments. *Composite Structures*. **144**, 80–85 (2016), doi:10.1016/j.compstruct.2016.02.053.

424. A. A. Ogale, M. Zhang, J. Jin, Recent advances in carbon fibers derived from biobased precursors. *J. Appl. Polym. Sci.* **133**, 3 (2016), doi:10.1002/app.43794.

425. P. Gérardin, New alternatives for wood preservation based on thermal and chemical modification of wood— a review. *Annals of Forest Science*. **73**, 559–570 (2016), doi:10.1007/s13595-015-0531-4.

426. K.-C. Mahnert, U. Hundhausen, A review on the protection of timber bridges. *Wood Material Science & Engineering*. **13**, 152–158 (2017), doi:10.1080/17480272.2017.1403955.

427. D. Sandberg, A. Kutnar, G. Mantanis, Wood modification technologies - a review. *iForest*. **10**, 895–908 (2017), doi:10.3832/ifor2380-010.

428. I. Burgert, M. Chanana, V. Merk, *Mineralized wood materials and methods providing mineralized wood materials - European Patent Office EP 2937193 A1* (24.04.2014).

429. D. Barber, in *Structures Congress 2017*, J. G. Soules, Ed. (American Society of Civil Engineers, Reston, 2017), pp. 556–569.

430. H. Ohashi, S. Igarashi, T. Nagaoka, Development of wood structural elements for fire resistant buildings. *Fire Engineering*. **9**, 126–137 (2018), doi:10.1108/JSFE-11-2016-0019.

Appendix

A Material Scores and Data

A.1 Durability

Material			Durability in the Marine Environment						
Category	Subcategory		Corrosion Resistance	Resistance to Degradation by Marine Organisms	Fatigue Resistance	Resistance to Stress Corrosion Cracking	UV Resistance	Moisture Resistance	Durability Score
Metals	Carbon Steels		1	3	3	2	5	5	3.00
Metals	Stainless Steels		4	3	3	4	5	5	4.00
Metals	Aluminum Alloys		4	3	2	3	5	5	3.77
Metals	Titanium Alloys		5	5	3	5	5	5	4.85
Metals	Nickel Alloys		5	5	2	5	5	5	4.77
Concrete	Blended Cement	Steel	4	5	4	3	5	5	4.38
Concrete	Blended Cement	Stainless Steel	5	5	4	4	5	5	4.77
Concrete	Blended Cement	GFRP	5	5	4	4	5	4	4.54
Concrete	Blended Cement	CFRP	5	5	4	5	5	5	4.92
Concrete	Alkali Activated Cement	Steel	4	5	4	3	5	5	4.38
Concrete	Alkali Activated Cement	Stainless Steel	5	5	4	4	5	5	4.77
Concrete	Alkali Activated Cement	GFRP	5	5	4	4	5	4	4.54
Concrete	Alkali Activated Cement	CFRP	5	5	4	5	5	5	4.92
Concrete	Calcium Sulfo-aluminate Cement	Steel	3	5	4	3	5	5	4.15
Concrete	Calcium Sulfo-aluminate Cement	Stainless Steel	5	5	4	4	5	5	4.77
Concrete	Calcium Sulfo-aluminate Cement	GFRP	5	5	4	4	5	4	4.54
Concrete	Calcium Sulfo-aluminate Cement	CFRP	5	5	4	5	5	5	4.92
Composites	Glass Fiber	Epoxy	5	5	3	3	3	3	3.92
Composites	Glass Fiber	Phenolic	5	5	3	3	3	3	3.92
Composites	Glass Fiber	Polyester	5	5	3	3	3	2	3.69
Composites	Glass Fiber	Vinyl Ester	5	5	3	3	3	4	4.15
Composites	Glass Fiber	Commodity Plastic	5	5	3	3	2	3	3.85
Composites	Glass Fiber	Engineering Plastic	5	5	3	3	2	3	3.85
Composites	Carbon Fiber	Epoxy	5	5	4	5	3	4	4.54
Composites	Carbon Fiber	Phenolic	5	5	4	5	3	4	4.54
Composites	Carbon Fiber	Polyester	5	5	4	5	3	3	4.31
Composites	Carbon Fiber	Vinyl Ester	5	5	4	5	3	2	4.08
Composites	Carbon Fiber	Commodity Plastic	5	5	4	5	2	4	4.46
Composites	Carbon Fiber	Engineering Plastic	5	5	4	5	2	4	4.46
Composites	Natural Fiber	Epoxy	5	4	3	2	2	1	3.00
Composites	Natural Fiber	Phenolic	5	4	3	2	2	1	3.00
Composites	Natural Fiber	Polyester	5	4	3	2	2	1	3.00
Composites	Natural Fiber	Vinyl Ester	5	4	3	2	2	1	3.00
Composites	Natural Fiber	Commodity Plastic	5	4	3	2	1	1	2.92
Composites	Natural Fiber	Engineering Plastic	5	4	3	2	1	1	2.92
Composites	Basalt Fiber	Epoxy	5	5	3	4	3	3	4.08
Composites	Basalt Fiber	Phenolic	5	5	3	4	3	3	4.08
Composites	Basalt Fiber	Polyester	5	5	3	4	3	2	3.85
Composites	Basalt Fiber	Vinyl Ester	5	5	3	4	3	4	4.31
Composites	Basalt Fiber	Commodity Plastic	5	5	3	4	2	3	4.00
Composites	Basalt Fiber	Engineering Plastic	5	5	3	4	2	3	4.00
Timber	Softwood		5	1	4	3	4	1	2.69
Timber	Hardwood Non-Tropical		5	2	4	3	4	2	3.15
Timber	Hardwood Tropical		5	3	4	4	4	4	4.00

A.2 Economics & Costs

Material			Economics & Costs								
Category	Subcategory		Material Costs	Ease of Manu-facture	Maintenance Cost - Vulnerability	Maintenance Cost - Repairability	Reaction to Fire	Resistance to Fire	Performance Uncertanty	Projected Price Develop-ments	Economics Score
Metals	Carbon Steels		5	4	4	5	5	2	5	3	4.25
	Stainless Steels		2	3	4	4	5	2	4	2	3.31
	Aluminum Alloys		4	4	3	4	5	2	4	2	3.56
	Titanium Alloys		2	3	4	2	5	5	5	2	3.38
	Nickel Alloys		1	4	4	5	5	2	4	1	3.31
Concrete	Blended Cement	Steel	5	5	4	4	5	4	4	3	4.31
		Stainless Steel	4	5	4	4	5	4	4	2	4.06
		GFRP	4	4	4	4	5	4	2	3	3.94
		CFRP	5	4	4	4	5	4	3	3	4.19
	Alkali Activated Cement	Steel	5	5	4	4	5	5	2	5	4.44
		Stainless Steel	4	5	4	4	5	5	1	4	4.13
		GFRP	5	4	4	4	5	5	1	5	4.31
		CFRP	5	4	4	4	5	5	1	5	4.31
	Calcium Sulfo-aluminate Cement	Steel	5	4	4	4	5	3	2	4	4.06
		Stainless Steel	4	4	4	4	5	3	1	3	3.75
		GFRP	4	3	4	4	5	3	1	4	3.75
		CFRP	5	3	4	4	5	3	1	4	3.94
Composites	Glass Fiber	Epoxy	3	4	3	4	3	3	3	2	3.19
		Phenolic	3	4	3	4	4	3	3	2	3.31
		Polyester	2	4	3	4	2	3	3	2	2.88
		Vinyl Ester	2	4	3	4	3	3	3	2	3.00
		Commodity Plastic	2	3	3	3	1	1	3	2	2.25
		Engineering Plastic	2	3	3	3	1	1	3	2	2.25
	Carbon Fiber	Epoxy	4	4	3	4	3	3	3	3	3.44
		Phenolic	3	4	3	4	4	3	3	3	3.38
		Polyester	3	4	3	4	2	3	3	3	3.13
		Vinyl Ester	3	4	3	4	3	3	1	3	3.13
		Commodity Plastic	3	3	3	3	1	1	3	3	2.50
		Engineering Plastic	3	3	3	3	1	1	3	3	2.50
	Natural Fiber	Epoxy	1	4	3	4	1	1	1	3	2.25
		Phenolic	1	4	3	4	1	1	1	3	2.25
		Polyester	1	4	3	4	1	1	1	3	2.25
		Vinyl Ester	1	4	3	4	1	1	1	3	2.25
		Commodity Plastic	1	3	3	3	1	1	1	3	2.00
		Engineering Plastic	1	3	3	3	1	1	1	3	2.00
	Basalt Fiber	Epoxy	3	4	3	4	3	3	1	2	3.06
		Phenolic	3	4	3	4	4	3	1	2	3.19
		Polyester	2	4	3	4	2	3	1	2	2.75
		Vinyl Ester	2	4	3	4	3	3	1	2	2.88
		Commodity Plastic	2	3	3	3	1	1	1	2	2.13
		Engineering Plastic	1	3	3	3	1	1	1	2	1.94
Timber	Softwood		5	3	3	4	2	3	5	1	3.44
	Hardwood Non-Tropical		4	2	3	4	2	3	5	1	3.19
	Hardwood Tropical		4	2	3	4	2	3	5	1	3.19

A.3 Sustainability & Environmental Impacts

Category	Subcategory		Raw Material Renewability	Recycling Approach	EI of Production on Human Health	EI of Production on Ecosystems	EI of Production on Resources	Sustainability Score
Metals	Carbon Steels		1	5	2	2	1	2.45
Metals	Stainless Steels		1	5	1	1	1	2.09
Metals	Aluminum Alloys		1	5	1	1	1	2.09
Metals	Titanium Alloys		1	5	1	1	1	2.09
Metals	Nickel Alloys		1	5	1	1	1	2.09
Concrete	Blended Cement	Steel	1	2	4	5	4	3.09
Concrete	Blended Cement	Stainless Steel	1	3	1	3	1	1.91
Concrete	Blended Cement	GFRP	1	1	5	5	5	3.18
Concrete	Blended Cement	CFRP	1	1	5	5	5	3.18
Concrete	Alkali Activated Cement	Steel	1	1	4	5	4	2.82
Concrete	Alkali Activated Cement	Stainless Steel	1	1	1	3	1	1.36
Concrete	Alkali Activated Cement	GFRP	1	1	5	5	5	3.18
Concrete	Alkali Activated Cement	CFRP	1	1	5	5	5	3.18
Concrete	Calcium Sulfo-aluminate Cement	Steel	1	1	4	4	4	2.64
Concrete	Calcium Sulfo-aluminate Cement	Stainless Steel	1	1	1	3	1	1.36
Concrete	Calcium Sulfo-aluminate Cement	GFRP	1	1	5	5	5	3.18
Concrete	Calcium Sulfo-aluminate Cement	CFRP	1	1	5	5	5	3.18
Composites	Glass Fiber	Epoxy	1	2	3	3	3	2.36
Composites	Glass Fiber	Phenolic	1	2	3	3	3	2.36
Composites	Glass Fiber	Polyester	1	2	2	2	2	1.82
Composites	Glass Fiber	Vinyl Ester	1	2	3	4	4	2.73
Composites	Glass Fiber	Commodity Plastic	1	2	3	3	3	2.36
Composites	Glass Fiber	Engineering Plastic	1	2	2	2	2	1.82
Composites	Carbon Fiber	Epoxy	1	2	4	4	3	2.73
Composites	Carbon Fiber	Phenolic	1	2	4	4	4	2.91
Composites	Carbon Fiber	Polyester	1	2	4	4	3	2.73
Composites	Carbon Fiber	Vinyl Ester	1	2	5	5	4	3.27
Composites	Carbon Fiber	Commodity Plastic	1	2	4	4	3	2.73
Composites	Carbon Fiber	Engineering Plastic	1	2	4	4	3	2.73
Composites	Natural Fiber	Epoxy	3	2	2	2	2	2.18
Composites	Natural Fiber	Phenolic	3	2	2	2	2	2.18
Composites	Natural Fiber	Polyester	3	2	2	1	2	2.00
Composites	Natural Fiber	Vinyl Ester	3	2	2	2	2	2.18
Composites	Natural Fiber	Commodity Plastic	3	2	2	2	2	2.18
Composites	Natural Fiber	Engineering Plastic	3	2	1	1	2	1.82
Composites	Basalt Fiber	Epoxy	1	2	3	3	4	2.55
Composites	Basalt Fiber	Phenolic	1	2	3	3	3	2.36
Composites	Basalt Fiber	Polyester	1	2	3	2	2	2.00
Composites	Basalt Fiber	Vinyl Ester	1	2	4	4	4	2.91
Composites	Basalt Fiber	Commodity Plastic	1	2	3	4	4	2.73
Composites	Basalt Fiber	Engineering Plastic	1	2	2	3	3	2.18
Timber	Softwood		5	5	5	1	5	4.27
Timber	Hardwood Non-Tropical		5	5	5	2	5	4.45
Timber	Hardwood Tropical		5	5	3	1	5	3.91

A.4 Future Availability

Material: Category	Material: Subcategory		Short-Term Raw Material Availability	Long-Term Raw Material Availability	Geographical Distribution of Reserves	Potential for Restrictive Government Regulation	Development of Recycling Infra-structure	Projected Growth of Competing Industries	Ease of Production Increase	Future Availability Score
Metals	Carbon Steels		2	5	4	5	5	5	5	4.44
Metals	Stainless Steels		1	2	1	2	5	1	3	2.19
Metals	Aluminum Alloys		1	5	1	4	5	3	3	3.25
Metals	Titanium Alloys		1	5	1	5	5	1	2	3.06
Metals	Nickel Alloys		2	2	4	2	5	1	2	2.81
Concrete	Blended Cement	Steel	3	5	4	5	4	5	4	4.31
Concrete	Blended Cement	Stainless Steel	1	2	1	2	4	1	3	2.00
Concrete	Blended Cement	GFRP	3	4	5	4	3	3	3	3.69
Concrete	Blended Cement	CFRP	3	4	5	4	3	3	3	3.69
Concrete	Alkali Activated Cement	Steel	3	5	4	4	4	3	2	3.81
Concrete	Alkali Activated Cement	Stainless Steel	1	2	1	2	4	1	2	1.94
Concrete	Alkali Activated Cement	GFRP	3	4	5	4	3	3	2	3.63
Concrete	Alkali Activated Cement	CFRP	3	4	5	4	3	3	2	3.63
Concrete	Calcium Sulfo-aluminate Cement	Steel	3	5	4	3	4	1	3	3.50
Concrete	Calcium Sulfo-aluminate Cement	Stainless Steel	1	2	1	2	4	1	3	2.00
Concrete	Calcium Sulfo-aluminate Cement	GFRP	3	4	4	3	3	1	3	3.13
Concrete	Calcium Sulfo-aluminate Cement	CFRP	3	4	4	3	3	1	3	3.13
Composites	Glass Fiber	Epoxy	3	4	5	4	3	3	3	3.69
Composites	Glass Fiber	Phenolic	3	4	5	4	3	3	3	3.69
Composites	Glass Fiber	Polyester	3	4	5	4	3	3	3	3.69
Composites	Glass Fiber	Vinyl Ester	3	4	5	4	3	3	3	3.69
Composites	Glass Fiber	Commodity Plastic	3	4	5	4	3	3	3	3.69
Composites	Glass Fiber	Engineering Plastic	3	4	5	4	3	3	3	3.69
Composites	Carbon Fiber	Epoxy	3	4	5	4	4	2	3	3.75
Composites	Carbon Fiber	Phenolic	3	4	5	4	4	2	3	3.75
Composites	Carbon Fiber	Polyester	3	4	5	4	4	2	3	3.75
Composites	Carbon Fiber	Vinyl Ester	3	4	5	4	4	2	3	3.75
Composites	Carbon Fiber	Commodity Plastic	3	4	5	4	4	2	3	3.75
Composites	Carbon Fiber	Engineering Plastic	3	4	5	4	4	2	3	3.75
Composites	Natural Fiber	Epoxy	3	4	5	4	3	3	2	3.63
Composites	Natural Fiber	Phenolic	3	4	5	4	3	3	2	3.63
Composites	Natural Fiber	Polyester	3	4	5	4	3	3	2	3.63
Composites	Natural Fiber	Vinyl Ester	3	4	5	4	3	3	2	3.63
Composites	Natural Fiber	Commodity Plastic	3	4	5	4	3	3	2	3.63
Composites	Natural Fiber	Engineering Plastic	3	4	5	4	3	3	2	3.63
Composites	Basalt Fiber	Epoxy	3	4	5	4	3	3	3	3.69
Composites	Basalt Fiber	Phenolic	3	4	5	4	3	3	3	3.69
Composites	Basalt Fiber	Polyester	3	4	5	4	3	3	3	3.69
Composites	Basalt Fiber	Vinyl Ester	3	4	5	4	3	3	3	3.69
Composites	Basalt Fiber	Commodity Plastic	3	4	5	4	3	3	3	3.69
Composites	Basalt Fiber	Engineering Plastic	3	4	5	4	3	3	3	3.69
Timber	Softwood		5	5	5	5	5	4	2	4.69
Timber	Hardwood Non-Tropical		5	5	5	5	5	4	2	4.69
Timber	Hardwood Tropical		5	5	5	1	5	4	1	4.13

A.5 Weighted and Unweighted Category and Total Scores

Material			Weighted						Equal Weights					
Category	Subcategory		Durability	Economics	Sustainability	Future Availability	Total Score	Rank	Durability	Economics	Sustainability	Future Availability	Total Score	Rank
Metals	Carbon Steels		3.00	4.25	2.45	4.44	3.56	15	3.17	3.78	2.20	4.43	3.39	16
Metals	Stainless Steels		4.00	3.31	2.09	2.19	2.76	43	4.00	3.63	1.80	2.14	2.89	35
Metals	Aluminum Alloys		3.77	3.56	2.09	3.25	3.13	32	3.67	3.88	1.80	3.14	3.12	28
Metals	Titanium Alloys		4.85	3.38	2.09	3.06	3.30	27	4.67	3.88	1.80	2.86	3.30	18
Metals	Nickel Alloys		4.77	3.31	2.09	2.81	3.18	30	4.50	3.75	1.80	2.57	3.16	27
Concrete	Blended Cement	Steel	4.38	4.31	3.09	4.31	4.03	2	4.33	4.13	3.20	4.29	3.99	1
Concrete	Blended Cement	Stainless Steel	4.77	4.06	1.91	2.00	2.93	38	4.67	4.00	1.80	2.00	3.12	29
Concrete	Blended Cement	GFRP	4.54	3.94	3.18	3.69	3.81	8	4.50	3.50	3.40	3.57	3.74	6
Concrete	Blended Cement	CFRP	4.92	4.19	3.18	3.69	3.93	3	4.83	3.75	3.40	3.57	3.89	2
Concrete	Alkali Activated Cement	Steel	4.38	4.44	2.82	3.81	3.79	9	4.33	4.00	3.00	3.57	3.73	8
Concrete	Alkali Activated Cement	Stainless Steel	4.77	4.13	1.36	1.94	2.78	42	4.67	3.75	1.40	1.86	2.92	32
Concrete	Alkali Activated Cement	GFRP	4.54	4.31	3.18	3.63	3.83	7	4.50	3.63	3.40	3.43	3.74	7
Concrete	Alkali Activated Cement	CFRP	4.92	4.31	3.18	3.63	3.92	6	4.83	3.63	3.40	3.43	3.82	4
Concrete	Calcium Sulfo-aluminate Cement	Steel	4.15	4.06	2.64	3.50	3.52	18	4.17	3.63	2.80	3.29	3.47	13
Concrete	Calcium Sulfo-aluminate Cement	Stainless Steel	4.77	3.75	1.36	2.00	2.75	44	4.67	3.38	1.40	2.00	2.86	36
Concrete	Calcium Sulfo-aluminate Cement	GFRP	4.54	3.75	3.18	3.13	3.57	14	4.50	3.13	3.40	3.00	3.51	12
Concrete	Calcium Sulfo-aluminate Cement	CFRP	4.92	3.94	3.18	3.13	3.69	10	4.83	3.25	3.40	3.00	3.62	10
Composites	Glass Fiber	Epoxy	3.92	3.19	2.36	3.69	3.35	25	3.67	3.00	2.40	3.57	3.16	26
Composites	Glass Fiber	Phenolic	3.92	3.31	2.36	3.69	3.37	24	4.33	3.13	2.80	3.57	3.46	14
Composites	Glass Fiber	Polyester	3.69	2.88	1.82	3.69	3.12	33	2.83	2.00	2.20	3.43	2.62	39
Composites	Glass Fiber	Vinyl Ester	4.15	3.00	2.73	3.69	3.48	21	3.83	2.75	2.60	3.57	3.19	24
Composites	Glass Fiber	Commodity Plastic	3.85	2.25	2.36	3.69	3.22	28	3.67	3.13	2.40	3.57	3.19	23
Composites	Glass Fiber	Engineering Plastic	3.85	2.25	1.82	3.69	3.08	34	4.33	3.13	3.00	3.57	3.51	11
Composites	Carbon Fiber	Epoxy	4.54	3.44	2.73	3.75	3.65	12	2.83	2.00	2.20	3.43	2.62	39
Composites	Carbon Fiber	Phenolic	4.54	3.38	2.91	3.75	3.69	11	3.83	2.88	2.40	3.57	3.17	25
Composites	Carbon Fiber	Polyester	4.31	3.13	2.73	3.75	3.56	16	3.50	2.75	1.80	3.57	2.91	33
Composites	Carbon Fiber	Vinyl Ester	4.08	3.13	3.27	3.75	3.63	13	4.17	2.88	2.80	3.57	3.35	17
Composites	Carbon Fiber	Commodity Plastic	4.46	2.50	2.73	3.75	3.52	19	2.83	2.00	2.00	3.43	2.57	42
Composites	Carbon Fiber	Engineering Plastic	4.46	2.50	2.73	3.75	3.52	19	3.67	2.50	2.00	3.57	2.93	31
Composites	Natural Fiber	Epoxy	3.00	2.25	2.18	3.63	2.94	35	3.83	2.88	2.80	3.57	3.27	20
Composites	Natural Fiber	Phenolic	3.00	2.25	2.18	3.63	2.94	35	4.00	2.75	3.40	3.57	3.43	15
Composites	Natural Fiber	Polyester	3.00	2.25	2.00	3.63	2.89	39	2.83	2.00	2.20	3.43	2.62	39
Composites	Natural Fiber	Vinyl Ester	3.00	2.25	2.18	3.63	2.94	35	4.00	2.63	3.00	3.57	3.30	19
Composites	Natural Fiber	Commodity Plastic	2.92	2.00	2.18	3.63	2.89	40	3.50	2.13	2.40	3.57	2.90	34
Composites	Natural Fiber	Engineering Plastic	2.92	2.00	1.82	3.63	2.79	41	4.17	2.25	2.80	3.57	3.20	21
Composites	Basalt Fiber	Epoxy	4.08	3.06	2.55	3.69	3.42	22	2.67	1.75	2.20	3.43	2.51	43
Composites	Basalt Fiber	Phenolic	4.08	3.19	2.36	3.69	3.39	23	3.67	1.88	2.80	3.57	2.98	30
Composites	Basalt Fiber	Polyester	3.85	2.75	2.00	3.69	3.19	29	3.50	2.13	1.80	3.57	2.75	38
Composites	Basalt Fiber	Vinyl Ester	4.31	2.88	2.91	3.69	3.55	17	4.17	2.25	2.80	3.57	3.20	21
Composites	Basalt Fiber	Commodity Plastic	4.00	2.13	2.73	3.69	3.33	26	2.67	1.75	1.80	3.43	2.41	44
Composites	Basalt Fiber	Engineering Plastic	4.00	1.94	2.18	3.69	3.17	31	3.67	1.75	2.20	3.57	2.80	37
Timber	Softwood		2.69	3.44	4.27	4.69	3.93	4	3.00	3.63	4.20	4.43	3.81	5
Timber	Hardwood Non-Tropical		3.15	3.19	4.45	4.69	4.06	1	3.33	3.38	4.40	4.43	3.88	3
Timber	Hardwood Tropical		4.00	3.19	3.91	4.13	3.92	5	4.00	3.38	3.80	3.71	3.72	9

A.6 Mechanical Strength, Cost and Environmental Impact Data

Category	Material / Subcategory		Compressive Strength [MPa]	kg/FU	Price [$/FU]	Environmental Impact [mPt/FU]			
						Human Health	Ecosystems	Resources	Total
Metals	Carbon Steels		400	3.25	2.24	253.4	84.8	513.3	851.4
Metals	Stainless Steels		485	2.72	17.09	9673.9	434.8	6983.7	17092.4
Metals	Aluminum Alloys		218	2.06	4.18	943.3	394.6	822.1	2160.0
Metals	Titanium Alloys		842	0.89	18.38	1417.9	590.4	834.6	2842.9
Metals	Nickel Alloys		765	1.87	26.45	6674.1	508.5	3757.7	10940.2
Concrete	Blended Cement	Steel	50	8.10	0.97	69.7	29.4	57.1	156.2
Concrete	Blended Cement	Stainless Steel	50	8.10	2.99	1182.6	67.9	850.5	2101.0
Concrete	Blended Cement	GFRP	50	7.82	2.74	47.8	22.8	28.2	98.8
Concrete	Blended Cement	CFRP	50	7.78	1.55	40.6	20.2	26.8	87.6
Concrete	Alkali Activated Cement	Steel	50	8.10	1.01	75.2	30.3	67.9	173.4
Concrete	Alkali Activated Cement	Stainless Steel	50	8.10	2.84	1191.0	68.8	860.2	2120.0
Concrete	Alkali Activated Cement	GFRP	50	7.82	2.59	53.3	23.7	38.9	115.9
Concrete	Alkali Activated Cement	CFRP	50	7.78	1.40	46.0	21.2	38.5	105.7
Concrete	Calcium Sulfo-aluminate Cement	Steel	45	9.00	1.08	85.8	37.4	63.4	186.6
Concrete	Calcium Sulfo-aluminate Cement	Stainless Steel	45	9.00	3.11	1323.0	80.3	945.0	2348.3
Concrete	Calcium Sulfo-aluminate Cement	GFRP	45	8.69	2.84	61.4	30.2	31.2	122.7
Concrete	Calcium Sulfo-aluminate Cement	CFRP	45	8.64	1.51	53.4	27.3	29.7	110.4
Composites	Glass Fiber	Epoxy	600	0.54	16.39	144.9	58.2	111.5	314.5
Composites	Glass Fiber	Phenolic	540	0.60	16.30	139.1	58.7	126.5	324.3
Composites	Glass Fiber	Polyester	420	0.76	19.32	186.0	90.7	141.0	417.8
Composites	Glass Fiber	Vinyl Ester	600	0.51	19.34	124.7	52.4	100.3	277.4
Composites	Glass Fiber	Commodity Plastic	420	0.70	19.56	131.3	54.9	109.0	295.1
Composites	Glass Fiber	Engineering Plastic	420	0.76	22.66	194.9	84.9	139.5	419.4
Composites	Carbon Fiber	Epoxy	1800	0.14	5.26	89.6	38.5	107.3	235.4
Composites	Carbon Fiber	Phenolic	1620	0.16	5.67	71.9	33.8	107.3	213.0
Composites	Carbon Fiber	Polyester	1260	0.20	7.19	94.6	48.4	130.4	273.5
Composites	Carbon Fiber	Vinyl Ester	1800	0.13	5.36	64.2	31.3	91.1	186.6
Composites	Carbon Fiber	Commodity Plastic	1260	0.18	7.20	77.5	37.0	122.4	237.0
Composites	Carbon Fiber	Engineering Plastic	1260	0.20	7.38	98.8	47.1	132.4	278.4
Composites	Natural Fiber	Epoxy	150	1.49	31.82	349.5	185.2	291.2	825.9
Composites	Natural Fiber	Phenolic	135	1.68	31.73	306.5	184.3	336.7	827.5
Composites	Natural Fiber	Polyester	105	2.11	37.35	416.9	294.8	345.3	1056.9
Composites	Natural Fiber	Vinyl Ester	150	1.38	36.58	272.3	162.3	247.6	682.2
Composites	Natural Fiber	Commodity Plastic	105	1.85	36.25	201.6	155.5	221.9	579.1
Composites	Natural Fiber	Engineering Plastic	105	2.09	43.69	451.3	273.7	342.6	1067.6
Composites	Basalt Fiber	Epoxy	600	0.56	16.91	129.4	56.7	107.2	293.3
Composites	Basalt Fiber	Phenolic	540	0.62	16.81	123.6	57.6	122.4	303.5
Composites	Basalt Fiber	Polyester	420	0.79	19.93	164.4	88.9	135.3	388.5
Composites	Basalt Fiber	Vinyl Ester	600	0.53	19.99	110.4	51.2	96.2	257.9
Composites	Basalt Fiber	Commodity Plastic	420	0.72	20.23	111.3	53.4	104.0	268.7
Composites	Basalt Fiber	Engineering Plastic	420	0.78	23.38	172.9	82.9	133.8	389.7
Timber	Softwood		54	1.81	1.78	17.3	277.2	12.1	306.6
Timber	Hardwood Non-Tropical		70	1.86	4.27	13.4	199.0	8.6	221.1
Timber	Hardwood Tropical		98	1.84	4.21	140.4	810.2	11.0	961.6

A.7 Availability Measures of Non-Renewable Raw Materials

Category	Material/Element	Raw Material	Reserves/P Ratio	Resource/P ratio	HHI of Reserves
Metals	Fe	Iron Ore	60.3	169.1	1586
	Al	Bauxite	107	286.3	1539
	Ni	Laterites (60%) Sulfite deposites (40 %)	34.7	57.8	1164
	Ti	Ilmenite & Rutile	125.8	>300	1514
	Mn	Manganese ore	43.1	Large	1840
	Mo	Molybdenite	66.1	85.5	3662
	Ta	Tantalum	>100	Adequate to meet needs	N/A
	Cu	Copper Ore	37.1	300 in US alone	1678
	Nb	Niobium	>70	Large	N/A
	Mg	Various	Virtually Unlimited	394.7	Widespread
	Cr	Chromite	16.8	Large	3890
	V	Vanadium ore	4	828.9	3246
	Zn	Zinc ore	18.5	160	1593
Concrete	Clinker	Limestone CaO	Abundant	Abundant	Widespread
	Clinker	Aluminous Clay	Abundant	Abundant	Widespread
	Clinker	Sand, calcium silicate	Abundant	Abundant	Widespread
	Blast Furnace Slag	See: Iron Ore	60.3	169.1	1586
	Course Aggregate	Stone	Abundant	Abundant	Widespread
	Fine Aggregate	Sand	Abundant	Abundant	Widespread
	Clay	Kaolin or Bentonite	Abundant	Abundant	Widespread
	Fly Ash Type C	See: Coal			
		Gypsum	Abundant	Abundant	Widespread
Composite	Basalt Fiber	Basalt Rock	Abundant	Abundant	Widespread
	Carbon Fiber	See: Oil & Natural Gas			
	Glass Fiber	Silica Sand	Abundant	Abundant	Widespread
	Glass Fiber	Limestone	Abundant	Abundant	Widespread
	Glass Fiber	Soda Ash	>1000	>3000	Widespread
	Glass Fiber	TiO2	131.4	303.030303	1514
	Vinyl Ester	See: Oil & Natural Gas			
	Epoxy	See: Oil & Natural Gas			
	Polyester	See: Oil & Natural Gas			
	Thermoplastic	See: Oil & Natural Gas			
Energy Related		Oil	50.7	128.2	957
		Natural Gas	52.8	115	998
		Coal	114		1382

B Life Cycle Assessment Data

For each material in the ranking the environmental impact of production (cradle-to-gate) was calculated using data from the econinvent 3.3 database adapted with data from recent literature. The final impact scores were calculated according to the ReCiPe 1.13 (Hierarchist) method. I

B.1 Metals

For the metals a number of different production processes are used around the globe. As the goal was to calculate an average impact of production, the global market process for each alloy was used (excl. impact from transport). To reflect the production of the specified alloy, the individual transformation processes used in the global market processes, were adapted to result in the desired alloy composition. Due to the large amount of data a complete depiction of all individual LCIs for each production method of each alloy would entail, only the changes made to the individual processes are described for the metal alloys instead of the entire LCIs.

B.1.1 Carbon Steel S355J2 / 1.0553

Original Files

Steel, low-alloyed {GLO}| market for | Alloc Def, U

Steel, low-alloyed {CA-QC}| steel production, electric, low-alloyed | Alloc Def, U

Steel, low-alloyed {RER}| steel production, converter, low-alloyed | Alloc Def, U

Steel, low-alloyed {RER}| steel production, electric, low-alloyed | Alloc Def, U

Steel, low-alloyed {RoW}| steel production, converter, low-alloyed | Alloc Def, U

Steel, low-alloyed {RoW}| steel production, electric, low-alloyed | Alloc Def, U

Adaptions

Removed Ferrochromium, high carbon, 68 % {GLO} market for

S355J0 does not contain any chromium so not required as raw material

Removed Ferronickel, 25 % Ni {GLO} market for (was 0.045 kg)

S355J0 does not contain nickel so not required as raw material

Increased content of Ferromanganese, high-coal, 74.5% Mn {GLO} market for (was 0.015278 kg)

0.021 kg/kg required to achieve Mn content of 1.6% in final alloy

Removed Molybdenite {GLO} market for (was 0.00059649 kg)

S355J0 does not contain molybdenum so not required as raw material

Increased manganese emissions to air (was 6.05E-7 kg)

8.5 E-7 kg/kg required to keep percentage constant with input of manganese

Removed chromium emissions to air (was 1.85E-7 kg)

No chromium input

Other waste, energy and input sources do not have a large effect on the final impact scores and where therefore left at the same values as before.

B.1.2 Stainless Steel X2CrNiMoN22-5-3 / 1.4462

Original Files

Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U

Steel, chromium steel 18/8 {RER}| steel production, converter, chromium steel 18/8 | Alloc Def, U

Steel, chromium steel 18/8 {RoW}| steel production, converter, chromium steel 18/8 | Alloc Def, U

Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8 | Alloc Def, U

Steel, chromium steel 18/8 {RoW}| steel production, electric, chromium steel 18/8 | Alloc Def, U

Adaptions

Decreased Ferronickel 25 % Ni {GLO} market for (was 0.32 kg)

> 0.2 kg/kg required to scale to final nickel content of 5%

Increased Ferrochromium, high-carbon, 68 & Cr {GLO} market for (was 0.26471)

> 0.3235 kg/kg required for final chromium content of 22%

Added Ferromanganese, high-coal, 74.5 % Mn {GLO} market for

> 0.021 kg/kg required to achieve the desired content of Mn which was estimated to be the same as in CS

Added Molybdenum trioxide {GLO} production

> 0.045 kg/kg MoOx is required for 0.03 kg/kg content of molybdenum in final product (stochiometric calculation)
>
> MoOx is smelted to ferromolybdenum which is added to steel. However no ferro-molybdenum process exists.

Increased waste manganese emissions to air (was 6.05E-7 kg)

> 8.5 E-7 kg/kg required to keep percentage constant with input of manganese

Increased chromium emissions to air (was 1.81 E-7 kg)

> 2.26E-7 kg/kg required to keep percentage constant with input of chromium

Other waste, energy and input sources do not have a large effect on the final impact scores and where therefore left at the same values as before.

B.1.3 Aluminum Alloy AlMg4.5Mn / Alloy 5083

Original Files

Aluminium alloy, AlMg3 {GLO}| market for | Alloc Def, U

Aluminium alloy, AlMg3 {RER}| production | Alloc Def, U

Aluminium alloy, AlMg3 {RoW}| production | Alloc Def, U

Adaptions

Decreased Chromium {GLO} market for (was 0.00305 kg)

0.0015 kg/kg required to achieve final chromium content of 0.15%

Increased Manganese {GLO} market for (was 0.00508 kg)

0.007 kg/kg required to achieve final manganese content of 0.7%

Increased Magnesium {GLO} market for (was 0.0305 kg)

0.044 kg/kg required to achieve final magnesium content of 4.4%

Decreased Aluminum, cast alloy {GLO} market for (was 0.965 kg)

0.947kg/kg required to achieve final aluminum content of 94.7%

Other waste, energy and input sources do not have a large effect on the final impact scores and where therefore left at the same values as before.

B.1.4 Titanium Alloy Ti 6Al-4V GR5 / 3.7165

Original File

Titanium, primary {GLO}| production | Alloc Def, U

Dataset includes production of Ti-sponge from $TiCl_4$ and Mg and the remelting of the sponge with the vacuum arc process. Alloying elements are added after sponge formation.

Adaptions

Decreased Magnesium {GLO} market for (was 0.016 kg)

0.01424 kg/kg required to achieve titanium content of 89% final product

Decreased Titanium tetrachloride{GLO} production (was 4 kg)

3.56 kg/kg required to achieve titanium content of 89% final product

Added Aluminum, primary, ingot {RoW} production

0.06 kg/kg required for final aluminum content of 6%

In reality the aluminum is added as powder, but no better aluminum input was found

Added Iron pellet {GLO} market for

0.004 kg/kg required for final iron content of 0.4%

Vanadium impact is added separately to the values calculated with the process described above

According to the Idemat Database from TU Delft production of 1 kg V causes 4.158 Pt of damage with the Recipe method (Human Health 1.91736; Ecosystems 0.83728; Resources 1.40351)

4% percent of vanadium in the final alloy lead to an additional 0.16623 points of damage (HH 0.07669; Ecosys 0.03349; Res 0.05614)

B.1.5 Nickle-Copper Alloy NiCu30Al / 2.4375

Original Files

Iron-nickel-chromium alloy {GLO}| market for | Alloc Def, U

Iron-nickel-chromium alloy {RER}| production | Alloc Def, U

Iron-nickel-chromium alloy {RoW}| production | Alloc Def, U

Adaptions

Removed Iron Scrap, sorted, pressed {GLO} market for Alloc, Def, U (was 0.474 kg)

No extra addition of iron necessary

Increased Nickel, 99.5 % {GLO} market for alloc Def, U (was 0.32 kg)

0.65327kg/kg required for final nickel content of 65%

Removed Ferrochromium, high-carbon, 68 % Ct {GLO} market for (was 0.309 kg)

No chromium present in Monel K 500

Added Copper {GLO} market for

0.3 kg/kg required for final copper content of 30%

Added Titanium primary {GLO} market for

0.006 kg/kg required for final titanium content of 0.6%

Added Aluminum primary, ingot {IAI Area, EU27 & EFTA/GLO} market for

0.027 kg/kg required for final aluminum content of 2.7%

Added Ferromanganese, high-coal, 74. 5 % Mn {GLO} market for

0.02 kg/kg added for the maximum final iron and manganese content of 2% present in the alloy

Increased nickel emissions to air (was 7.07E-7 kg)

1.44E-6 kg/kg to keep percentage constant in relation to input of nickel

Removed chromium emissions to air (was 1.25E-6 kg)

No chromium in Monel K 500

B.2 Composites

For the FRPCs the LCIs were calculated for 1 m^3 of material assuming a 95% use efficiency for raw fibers and resins.

	Fiber	Glass				Carbon				Natural				Basalt			
	Resin	**E**	**PE**	**VE**	**TP**	**E**	**PE**	**VE**	**TP**	**E**	**PE**	**VE**	**TP**	**E**	**PE**	**VE**	**TP**
	Weight of 1m3 [kg]	1905	1915	1845	1870	1515	1525	1455	1480	1360	1370	1300	1325	2035	2045	1975	2000
Life Cycle Inventory for 1 m3 Composite																	
Materials [kg]	**Comment**																
Epoxy resin, liquid {GLO}| market for		668.4	x	x	x	668.4	x	x	x	668.4	x	x	x	668.4	x	x	x
Polyester resin, unsaturated {GLO}| market for		x	678.9	x	x	x	678.9	x	x	x	678.9	x	x	x	678.9	x	x
Bisphenol A epoxy based vinyl ester resin {GLO}| market for		x	x	605.3	x	x	x	605.3	x	x	x	605.3	x	x	x	605.3	x
Polycarbonate {GLO}| market for		x	x	x	631.6	x	x	x	631.6	x	x	x	631.6	x	x	x	631.6
Chemical, organic {GLO}| market for	Estimation for extender, additives and peroxides	47.6	47.9	46.1	46.8	37.9	38.1	36.4	37.0	34.0	34.3	32.5	33.1	50.9	51.1	49.7	50.0
Injection moulding {GLO}| market for	Estimation for process energy requirement	1905	1915	1845	1870	1515	1525	1455	1480	1360	1370	1300	1325	2035	2045	1975	2000
Glass fibre {GLO}| market for		1336.8	1336.8	1336.8	1336.8	x	x	x	x	x	x	x	x	x	x	x	x
Carbon Fiber	Impact values taken from Idemat Database from TU Delft	x	x	x	x	926.3	926.3	926.3	926.3	x	x	x	x	x	x	x	x
Jute fibre {GLO}| market for		x	x	x	x	x	x	x	x	763.2	763.2	763.2	763.2	x	x	x	x
Basalt Fiber {GLO}| market for		x	x	x	x	x	x	x	x	x	x	x	x	1473.7	1473.7	1473.7	1473.7
Emissions to Air [kg]																	
Hydrocarbons, aromatic, high pop.	Estimated for styrene emissions during curing of resin	x	0.101	0.090	x	x	0.101	0.090	x	x	0.101	0.090	x	x	0.101	0.090	x
Waste to Waste Treamtent [kg]																	
Waste mineral wool, for final disposal {RoW}| market for	5% fiber loss	66.8	66.8	66.8	66.8	46.3	46.3	46.3	46.3	38.2	38.2	38.2	38.2	73.7	73.7	73.7	73.7

B.3 Cement and Concrete

B.3.1 Blended Cement

		Amount	Unit	Comment	Source
OUTPUT					
	Blended Cement Concrete	2300	kg	Weight of 1m3 standard concrete	[1]
INPUT					
	Materials/fuels				
	Ethylene oxide	1.799998663	kg		Ecoinvent
	Fatty alcohol	0.204999848	kg	Extrapolated value. Air-entrainers	Ecoinvent
	Synthetic rubber	0.007129995	kg	Literature value. From ecoinvent dataset "concrete production, normal"	Ecoinvent
	Lubricating oil	0.011899991	kg	Literature value. From ecoinvent dataset "concrete production, normal"	Ecoinvent
	Sand	806.3975969	kg		[1], Ecoinvent
	Steel, low-alloyed, hot rolled	0.023799982	kg	Literature value. From ecoinvent dataset ""concrete production, normal""	Ecoinvent
	Gravel	959.9971391	kg		[1], Ecoinvent
	Concrete mixing factory	4.57E-07	p	Literature value. From ecoinvent dataset ""concrete production, normal""	Ecoinvent
	Chemical, organic	1.289999042	kg	Extrapolated value. Water reducing admixture	Ecoinvent
	Tap water	152	kg	Split into regions according to global production volumes given in Ecoinvent	[1], [2], Ecoinvent
	Cement, blast furnace slag 36-65%	380	kg	Split into regions according to global production volumes given in Ecoinvent	[1], [2], Ecoinvent
	Electricity/heat				
	Diesel, burned in building machine	15.64270358	MJ	Energy use in ready-mix plant. Includes air emissions from diesel combustion	Ecoinvent
	Electricity, medium voltage	4.113996944	kWh	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent
	Heat, district or industrial, natural gas	10.6322621	MJ	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent
EMISSIONS				Overall Emissions account for 0.01 mPt of impact	
& WASTE	**Emissions to air**				
	Water/m3	0.006141172	m3		Ecoinvent
	Emissions to water				
	Chlorides, unspecified	3.09E-09	kg		Ecoinvent
	Iron	1.55E-08	kg		Ecoinvent
	Suspended solids, unspecified	4.64E-07	kg		Ecoinvent
	Copper	1.55E-08	kg		Ecoinvent
	Oils, unspecified	2.32E-07	kg		Ecoinvent
	Waste to treatment				
	Wastewater from concrete production	0.034799974	m3	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent

Sources:

[1] P.L.J. Domone, J.M. Illston, Construction materials: Their nature and behaviour / edited by Peter Domone and John Illston, 4th ed., Spon Press, London, New York, 2010.

[2] P.B. Bamforth, Properties of concrete for use in Eurocode 2: How to optimise the engineering properties of concrete in design to Eurocode 2, Concrete Center, Surrey, 2008.

B.3.2 Alkali Activated Cement

		Amount	Unit	Comment	Source
OUTPUT					
	Fly Ash	1	kg	Impacts stem from the drying and stocking of FA so it can be used as a building product	
INPUT					
	Materials/Fuels				
	Transport, freight, lorry >32 metric ton	0.003	tkm		[1]
	Heavy fuel oil	0.00000103	kg		[1]
	Electricity/heat				
	Electricity, medium voltage	0.00682	kWh		[1]
	Heat, district or industrial, natural gas	0.29	MJ		[1]
EMISSIONS & WASTE	**Emissions to air**				
	Particulates, unspecified	0.0000323	kg		[1]
	Sulfur oxides	9.13E-08	kg		[1]
	Hydrogen sulfide	0.0000175	kg		[1]
	Carbon monoxide	0.00000905	kg		[1]
	Waste to treatment				
	Fly ash and scrubber sludge	0.0000848	m3		[1]

		Amount	Unit	Comment	Source
OUTPUT					
	Alkali Activated Concrete	2300	kg	Inputs not related to the raw materials were assumed to be the same as for BC concrete production	[2]
INPUT					
	Materials/Fuels				
	Ethylene oxide	1.799998663	kg		Ecoinvent
	Fatty alcohol	0.204999848	kg	Extrapolated value. Air-entrainers	Ecoinvent
	Synthetic rubber	0.007129995	kg	Literature value. From ecoinvent dataset "concrete production, normal"	Ecoinvent
	Lubricating oil	0.011899991	kg	Literature value. From ecoinvent dataset "concrete production, normal"	Ecoinvent
	Gravel	1170	kg		[2]
	Steel, low-alloyed, hot rolled	0.023799982	kg	Literature value. From ecoinvent dataset ""concrete production, normal""	Ecoinvent
	Sand	630	kg		[2]
	Concrete mixing factory	4.57E-07	p	Literature value. From ecoinvent dataset ""concrete production, normal""	Ecoinvent
	Fly Ash	444	kg	See above	[2]
	Sodium hydroxide, without water, in 50% solution state	35.552	kg	Calculated mass of NaOH 50% solution required to achieve 44 kg of 14M solution	[2]
	Sodium silicate, without water, in 37% solution state	111	kg		[2]
	Tap water	25.8	kg		[2]
	Chemical, organic	6.1	kg	For Plasticizer	[2]
	Electricity/heat				
	Diesel, burned in building machine	15.64270358	MJ	Energy use in ready-mix plant. Includes air emissions from diesel combustion.	Ecoinvent
	Electricity, medium voltage	4.113996944	kWh	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent
	Heat, district or industrial, natural gas	10.6322621	MJ	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent
EMISSIONS & WASTE	**Emissions to air**			Overall Emissions account for 0.01 mPt of impact	
	Water/m3	0.006141172	m3		Ecoinvent
	Emissions to water				
	Chlorides, unspecified	3.09E-09	kg		Ecoinvent
	Iron	1.55E-08	kg		Ecoinvent
	Suspended solids, unspecified	4.64E-07	kg		Ecoinvent
	Copper	1.55E-08	kg		Ecoinvent
	Oils, unspecified	2.32E-07	kg		Ecoinvent
	Waste to treatment				
	Wastewater from concrete production	0.034799974	m3	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent

Sources:

[1] Chen C, Habert G, Bouzidi Y, Jullien A, Ventura A. LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete. Resources, Conservation and Recycling 2010;54(12):1231–40

[2] M. Olivia, P.K. Sarker, H. Nikraz, Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete, Proceedings ICCBT2008 - A - 46 (2008) 5178–5530.

B.3.3 Calcium Sulfoaluminate Cement

		Amount	Unit	Comment	Source
OUTPUT					
	CSA Clinker	1	kg	This process was adapted to CSA production using the existing process "Clinker {Europe without Switzerland} production" from Ecoinvent as a basis	
INPUT					
	Materials/fuels				
	Water, unspecified natural origins	0.001619978	m3		Ecoinvent
	Light fuel oil	0.000330013	kg	Energy used in kiln reduced by 11.76 % (lower temp) compared to standard Clinker production	[1], [2], Ecoinvent
	Hard coal	0.031236543	kg	Energy used in kiln reduced by 11.76 % (lower temp) compared to standard Clinker production	[1], [2], Ecoinvent
	Natural gas, high pressure	0.000154083	m3	Energy used in kiln reduced by 11.76 % (lower temp) compared to standard Clinker production	[1], [2], Ecoinvent
	Heavy fuel oil	0.0225009	kg	Energy used in kiln reduced by 11.76 % (lower temp) compared to standard Clinker production	[1], [2], Ecoinvent
	Petroleum coke {GLO}	0.003450138	kg	Energy used in kiln reduced by 11.76 % (lower temp) compared to standard Clinker production	[1], [2], Ecoinvent
	Refractory, high aluminium oxide, packed	0.000136998	kg		Ecoinvent
	Refractory, basic, packed	0.000189997	kg		Ecoinvent
	Steel, chromium steel 18/8, hot rolled	5.85992E-05	kg		Ecoinvent
	Ammonia, liquid	0.000907988	kg		Ecoinvent
	Industrial machine, heavy, unspecified	3.75995E-05	kg		Ecoinvent
	Refractory, fireclay, packed	8.20989E-05	kg		Ecoinvent
	Tap water	0.339995463	kg		Ecoinvent
	Cement factory	6.26992E-12	p		Ecoinvent
	Lubricating oil	4.70994E-05	kg		Ecoinvent
	Lime	0.51515	kg		[3]
	Gravel	0.08582	kg		[3]
	Bauxite	0.6029	kg		[3]
	Lime, hydrated, loose weight	0.003919948	kg		Ecoinvent
	Gypsum, mineral	0.23167	kg		[3]
	Electricity/heat				
	Electricity, medium voltage	0.057999226	kWh	electrical power to operate cement plant, negligible overall impact	Ecoinvent
	Diesel, burned in building machine	0.013399821	MJ	fuel required for factory-internal transport of material	Ecoinvent
EMISSIONS & WASTE	**Emissions to air**				
	Copper	1.39998E-08	kg		Ecoinvent
	Cobalt	3.99995E-09	kg		Ecoinvent
	Mercury	3.29996E-08	kg		Ecoinvent
	Selenium	1.99997E-09	kg		Ecoinvent
	Lead	8.49989E-08	kg		Ecoinvent
	Arsenic	1.19998E-08	kg		Ecoinvent
	Particulates, > 10 um	5.65992E-06	kg		Ecoinvent
	Hydrogen chloride	6.30992E-06	kg		Ecoinvent
	Beryllium	2.99996E-09	kg		Ecoinvent
	Particulates, < 2.5 um	2.40997E-05	kg		Ecoinvent
	Nickel	4.99993E-09	kg		Ecoinvent
	Vanadium	4.99993E-09	kg		Ecoinvent
	Cadmium	6.99991E-09	kg		Ecoinvent
	Particulates, > 2.5 um, and < 10um	7.91989E-06	kg		Ecoinvent
	Water/m3	0.000293996	m3		Ecoinvent
	Chromium	1.44998E-09	kg		Ecoinvent
	Sulfur dioxide	0.000354995	kg		Ecoinvent
	Ammonia	2.27997E-05	kg		Ecoinvent
	Antimony	1.99997E-09	kg		Ecoinvent
	Thallium	1.29998E-08	kg		Ecoinvent
	Carbon monoxide, fossil	0.000416487	kg	emissions stemming from burning of fuel are reduced by 11.76% due to lower temperature requirements	[1], [2], Ecoinvent
	Carbon dioxide, biogenic	0.015099798	kg		Ecoinvent
	Zinc	5.99992E-08	kg		Ecoinvent
	Tin	8.99988E-09	kg		Ecoinvent
	Chromium VI	5.49993E-10	kg		Ecoinvent
	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	9.59987E-13	kg		Ecoinvent
	non-methane volatile organic compounds	5.63992E-05	kg		Ecoinvent
	Nitrogen oxides	0.000952979	kg	emissions stemming from burning of fuel are reduced by 11.76% due to lower temperature requirements	[1], [2], Ecoinvent
	Carbon dioxide, fossil	0.296129488	kg	60% of CO2 emissions are from decarbonization of limestone. Therefore, 40% are from burning of fuel. Reduced by 11.76 % compared to standard clinker production due to lower energy requirements	[1], [2], [4], Ecoinvent
	Carbon dioxide, fossil	0.308358165	kg	0.6 kg CO2/kg Limestone in kiln is produced.	[3], Ecoinvnet
	Methane, fossil	7.83561E-06	kg	emissions stemming from burning of fuel are reduced by 11.76% due to lower temperature requirements	[1], [2], Ecoinvent
	Emissions to water				
	Water	0.001665978	m3		Ecoinvent
	Waste to treatment				
	Inert waste, for final disposal	7.99989E-05	kg		Ecoinvent
	Municipal solid waste	4.49994E-05	kg		Ecoinvent

		Amount	Unit	Comment	Source
OUTPUT					
	CSA Cement	1	kg	This process was adapted to CSA Cement production using the existing process " Cement, Portland {Europe without Switzerland}| production" as a basis	
INPUT					
	Materials/fuels				
	Limestone, crushed, for mill	0.05	kg		[3], Ecoinvent
	Gypsum	0.160481928	kg		[3]
	Cement factory {GLO}| market for	5.36E-11	p		Ecoinvent
	Steel, low-alloyed	0.00011			Ecoinvent
	Ethylene glycol	0.00019	kg		Ecoinvent
	CSA Clinker	0.8395181	kg	see above	[3]
	Electricity/heat				
	Electricity, medium voltage	0.0376	kWh		Ecoinvent
EMISSIONS & WASTE	**Emissions to air**				
	Heat, waste	0.135	MJ		Ecoinvent

		Amount	Unit	Comment	Source
OUTPUT					
	Blended Cement Concrete	2300	kg	Inputs not related to the raw materials were assumed to be the same as for BC concrete production	
INPUT					
	Materials/fuels				
	Ethylene oxide	1.799998663	kg		Ecoinvent
	Fatty alcohol	0.204999848	kg	Extrapolated value. Air-entrainers	Ecoinvent
	Synthetic rubber	0.007129995	kg	Literature value. From ecoinvent dataset "concrete production, normal"	Ecoinvent
	Lubricating oil	0.011899991	kg	Literature value. From ecoinvent dataset "concrete production, normal"	Ecoinvent
	Sand	806.3975969	kg		[5], Ecoinvent
	Steel, low-alloyed, hot rolled	0.023799982	kg	Literature value. From ecoinvent dataset ""concrete production, normal""	Ecoinvent
	Gravel	959.9971391	kg		[5], Ecoinvent
	Concrete mixing factory	4.57E-07	p	Literature value. From ecoinvent dataset ""concrete production, normal""	Ecoinvent
	Chemical, organic	1.289999042	kg	Extrapolated value. Water reducing admixture	Ecoinvent
	Tap water	152	kg	Split into regions according to global production volumes given in Ecoinvent	[5], Ecoinvent
	Cement, blast furnace slag 36-65%	360	kg	see above	[5], Ecoinvent
	Electricity/heat				
	Diesel, burned in building machine	15.64270358	MJ	Energy use in ready-mix plant. Includes air emissions from diesel combustion.	Ecoinvent
	Electricity, medium voltage	4.113996944	kWh	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent
	Heat, district or industrial, natural gas	10.6322621	MJ	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent
EMISSIONS				Overall Emissions account for 0.01 mPt of impact	
& WASTE	**Emissions to air**				
	Water/m3	0.006141172	m3		Ecoinvent
	Emissions to water				
	Chlorides, unspecified	3.09E-09	kg		Ecoinvent
	Iron	1.55E-08	kg		Ecoinvent
	Suspended solids, unspecified	4.64E-07	kg		Ecoinvent
	Copper	1.55E-08	kg		Ecoinvent
	Oils, unspecified	2.32E-07	kg		Ecoinvent
	Waste to treatment				
	Wastewater from concrete production	0.034799974	m3	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent

Sources:

[1] Aranda M.A.G., de La Torre A.G. Sulfoaluminate cement. In: Pacheco-Torgal F, Jalali S, Labrincha J, John VM, editors. Eco-Efficient Concrete. Woodhead Publishing; 2013, p. 488–522.

[2] Gartner E. Industrially interesting approaches to “low-CO2” cements. Cement and Concrete Research 2004;34(9):1489–98

[3] Italcementi Group, ALIPRE - ALICEM: Environmental Product Declaration, 2012.

[4] K.L. Scrivener, V.M. John, E.M. Gartner, Eco-efficient cements: Potential, economically viable solutions for a low-CO2, cement-based materials industry, Paris, 2016.

[5] Lafarge SA, Aether - Lower Carbon Cements, 2014, http://www.aether-cement.eu/results.html, accessed 30 May 2018.

B.3.4 Rebar

B.3.4.1 Carbon Steel

		Amount	Unit	Comment	Source
OUTPUT					
	Reinforcing Steel	1	kg	Process taken directly from ecoinvent	

B.3.4.2 Glass Fiber Reinforced Epoxy

		Amount	Unit	Comment	Source
OUTPUT					
	Glass Fiber Reinforced Epoxy Composite	1905	kg	Weight of 1m3 of composite with a fiber volume fraction of 0.5	
INPUT					
	Materials/fuels				
	Epoxy resin, liquid	668.421053	kg		
	Chemical, organic	47.625	kg	Estimation for extender, additives and peroxides	Ecoinvent
	Injection moulding	1905	kg	Estimation for process energy requirement	Ecoinvent
	Glass fibre	1336.84211	kg		
EMISSIONS & WASTE	**Waste to Waste Treamtent [kg]**				
	Waste mineral wool, for final disposal	66.8421053	kg	5% fiber loss estimated during production	Ecoinvent

B.3.4.3 Duplex Stainless Steel

		Amount	Unit	Comment	Source
OUTPUT					
	Stainles Steel Duplex 1.4462	1	kg	This process was adapted to 1.4462 steel using the existing process "Steel, chromium steel 18/8 {RER}| steel production, converter, chromium steel 18/8" as a basis	
INPUT					
	Materials/fuels				
	Water, unspecified natural origin	0.0027	m3		Ecoinvent
	Ferronickel, 25% Ni	0.2	kg	0.2 kg/kg required to scale to final nickel content of 5%	[1]
	Dolomite	0.00275	kg		Ecoinvent
	Quicklime, in pieces, loose	0.0425	kg		[1]
	Ferrochromium, high-carbon, 68% Cr	0.32354	kg	0.3235 kg/kg required for final chromium content of 22%	Ecoinvent
	Blast oxygen furnace converter	1.3333E-11	p		Ecoinvent
	Iron ore, beneficiated, 65% Fe	0.022	kg		[1]
	Pig iron	0.52779	kg		[1]
	Oxygen, liquid	0.07145	kg		Ecoinvent
	Natural gas, high pressure	0.00096154	m3	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent
	Ferromanganese, high-coal, 74.5% Mn	0.021	kg		[1]
	Molybdenum trioxide	0.045	kg	0.045 kg/kg MoOx is required for 0.03 kg/kg content of molybdenum in final product	[1]
	Electricity/heat				
	Coke	0.00025	MJ		Ecoinvent
	Electricity, medium voltage	0.021944	kWh	Split into regions according to global production volumes given in Ecoinvent	Ecoinvent
EMISSIONS & WASTE	**Emissions to air**				
	Lead	5.15E-07	kg		Ecoinvent
	Particulates, < 2.5 um	0.0000475	kg		Ecoinvent
	Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	3.05E-14	kg		Ecoinvent
	PAH, polycyclic aromatic hydrocarbons	1.2E-10	kg		Ecoinvent
	Manganese	0.00000085	kg	Percentage kept constant with respect to input of manganese	[1]
	Copper	2.5E-08	kg		Ecoinvent
	Carbon dioxide, fossil	0.0756	kg		Ecoinvent
	Nitrogen oxides	0.0000125	kg		Ecoinvent
	Chromium	2.26E-07	kg	Percentage kept constant with respect to input of chromium	[1]
	Water/m3	0.000405	m3		Ecoinvent
	Carbon monoxide, fossil	0.00473	kg		Ecoinvent
	Emissions to water				
	Water, RoW	0.002295	m3		Ecoinvent
	Waste to treatment				
	Basic oxygen furnace waste	0.032077	kg		Ecoinvent
	Inert waste, for final disposal	0.0029	kg		Ecoinvent
	Dust, alloyed electric arc furnace steel	0.0010625	kg		Ecoinvent

B.3.4.4 Carbon Fiber Renforced Epoxy

		Amount	Unit	Comment	Source
OUTPUT					
	Glass Fiber Reinforced Epoxy Composite	1515	kg	Weight of 1m3 of composite with a fiber volume fraction of 0.5	
INPUT					
	Materials/fuels				
	Epoxy resin, liquid	668.421053	kg		
	Chemical, organic	37.9	kg	Estimation for extender, additives and peroxides	Ecoinvent
	Injection moulding	1515	kg	Estimation for process energy requirement	Ecoinvent
	Carbon Fiber	926.3	kg	Impact values for fibers taken from the Idemat Database of the TU Delft	[2]
EMISSIONS					
& WASTE	**Waste to Waste Treamtent [kg]**				
	Waste mineral wool, for final disposal	46.3	kg	5% fiber loss estimated during production	Ecoinvent

Sources:

[1]: Granta Material Intelligence. MaterialUniverse materials data. (2018); Available from: http://www.grantadesign.com/products/data/materialuniverse.htm.

[2]: Idemat Database. Idematapp File (2018); Available from: www.ecocostsvalue.com/EVR/img/Idematapp2018.xlsx

B.4 Timber

The LCAs of the different timbers were completed by directly using the original market files of the ecoinvent 3.3 database and removing all transport related impacts.

B.4.1 Softwoods

Original file used:

Sawnwood, softwood, dried (u=20%), planed {RER} market for

Comments:

Is most global approach for adding softwood, as individual species are not included in dataset.

RER and RoW data is exactly the same. No reason to have a global market

B.4.2 Non-Tropical Hardwoods

Original file used:

Sawnwood, lath, hardwood, dried (u=20%), planed {GLO} market for

Comments:

Presents the most global approach to estimate the impact of hardwood production, as there is no black locust data and the data on specific species such as oak or birch do not include the processing after harvest.

B.4.3 Tropical Hardwoods

Original file used:

Sawnwood, azobe from sustainable forest management, planed, air dried {GLO} market for

Comments:

This type of wood is also called ekki, so same species.